

On top of the ALPs

Milano Christmas Meeting 2023

[Blasi, Maltoni, Mariotti, Mimasu, Pagani, ST 2311.16048]



The Search of New Physics



2012: Higgs Boson Discovery

Standard Model is Complete!

Open Problems

- Strong CP problem
- Neutrino masses
- Dark Matter
- Naturalness

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Solutions:

- Heavy states
- Light elusive states

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 $\rightarrow m_a < f_a$

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

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



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

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

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Equations of motion

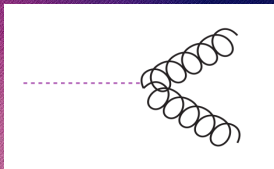
ALP = Pseudoscalar term + Contact term

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

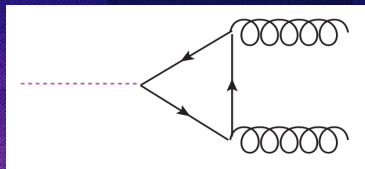
TOP-ALP vs Pseudoscalar

$$a \rightarrow gg(\gamma\gamma)$$

Blasi, Maltoni, Mariotti, Mimasu, Pagani, ST [2311.16048]
Bauer, Neubert, Thamm [1708.00443]



+



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

Only contact
interaction

Only Pseudoscalar

$2m_t > m_a$

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

Cancellation between contact
interaction and pseudoscalar!

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

Super-suppressed
w.r.t. single terms

About top-philic ALP monogamy

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

[Esser, Madigan, Sanz, Ubiali, 2303.17634]

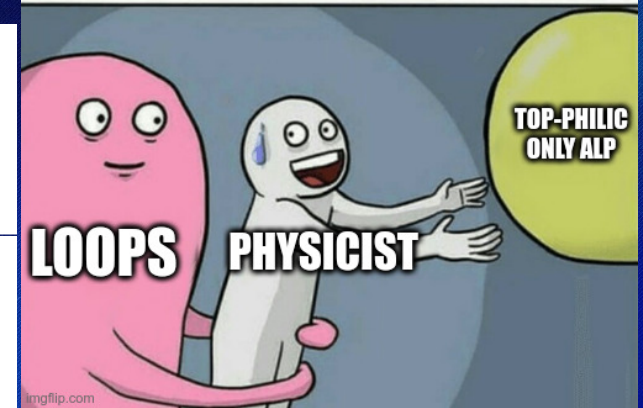
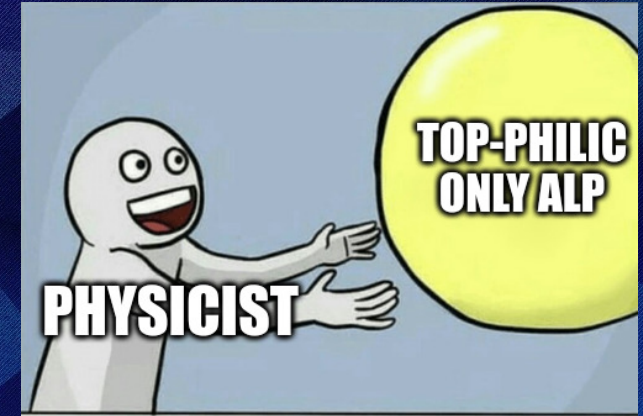
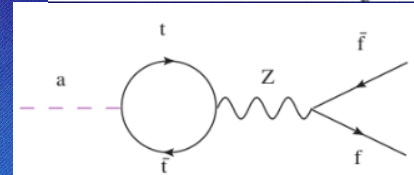
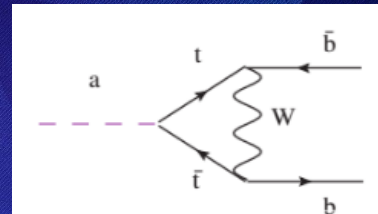
[Blasi, Maltoni, Mariotti, Mimasu, Pagani, ST [2311.16048]]

- Tree level: YES

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 [2311.16048]]
- Loops: NO [Bauer, Neubert, Renner, Schnubel Thamm, 2012.12272, 2110.10698]
[Bonilla, Brivio, Gavela, Sanz, 2107.11392]

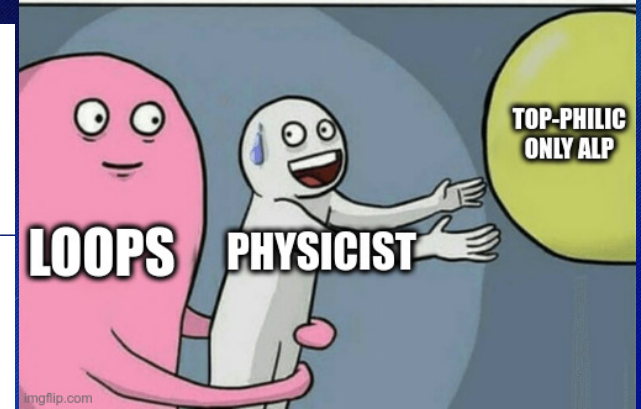
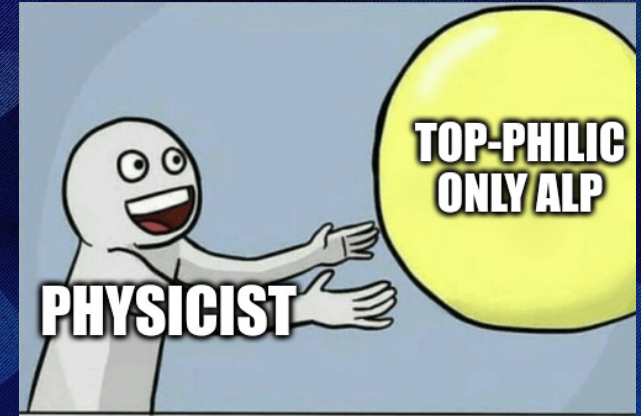
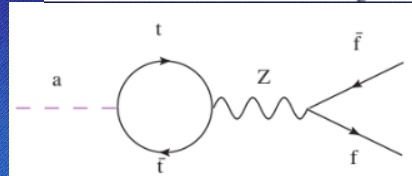
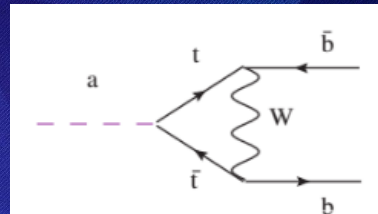


About top-philic ALP monogamy

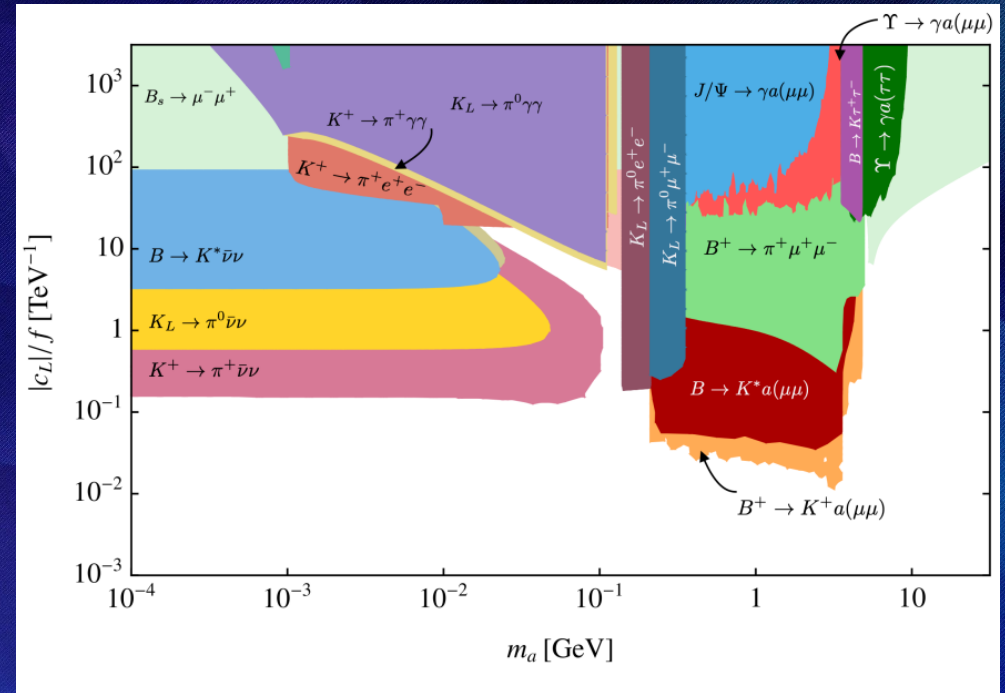
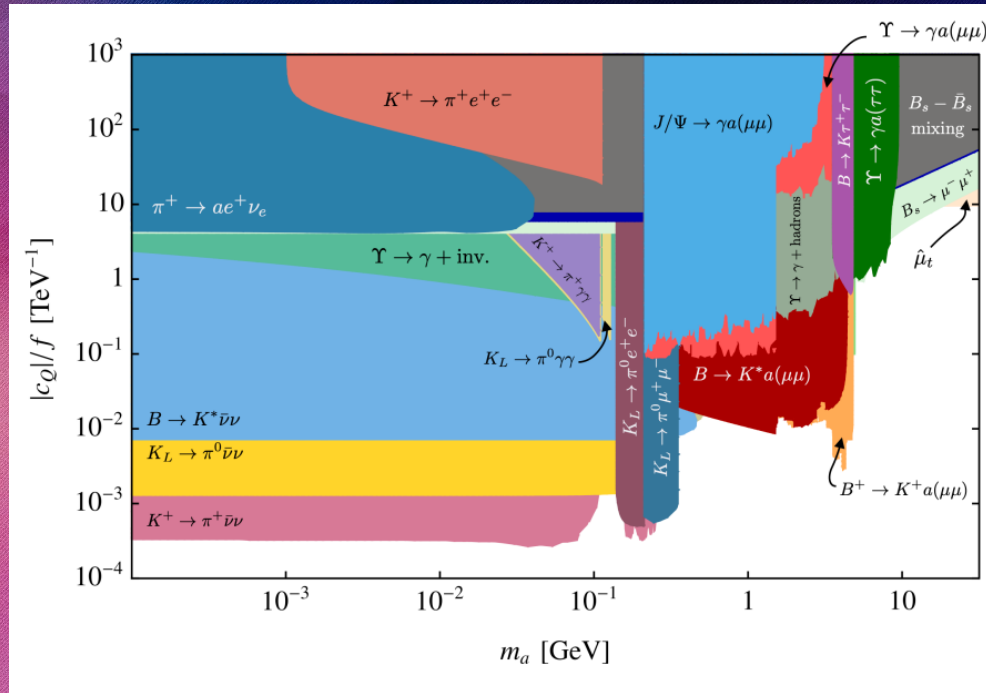
Can we have an ALP coupling only to top-quark?

- Tree level: YES [Esser, Madigan, Sanz, Ubiali, 2303.17634]
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$$\begin{cases} c_t(m_t) &= c_t(\Lambda) \left(1 - 9 \frac{y_t^2}{16\pi^2} \log \frac{\Lambda}{m_t} \right) \\ c_b(m_t) &= 5 c_t(\Lambda) \frac{y_t^2}{16\pi^2} \log \frac{\Lambda}{m_t} \\ c_f(m_t) &= -12 c_t(\Lambda) \frac{y_t^2}{16\pi^2} T_3^f \log \frac{\Lambda}{m_t} \end{cases}$$



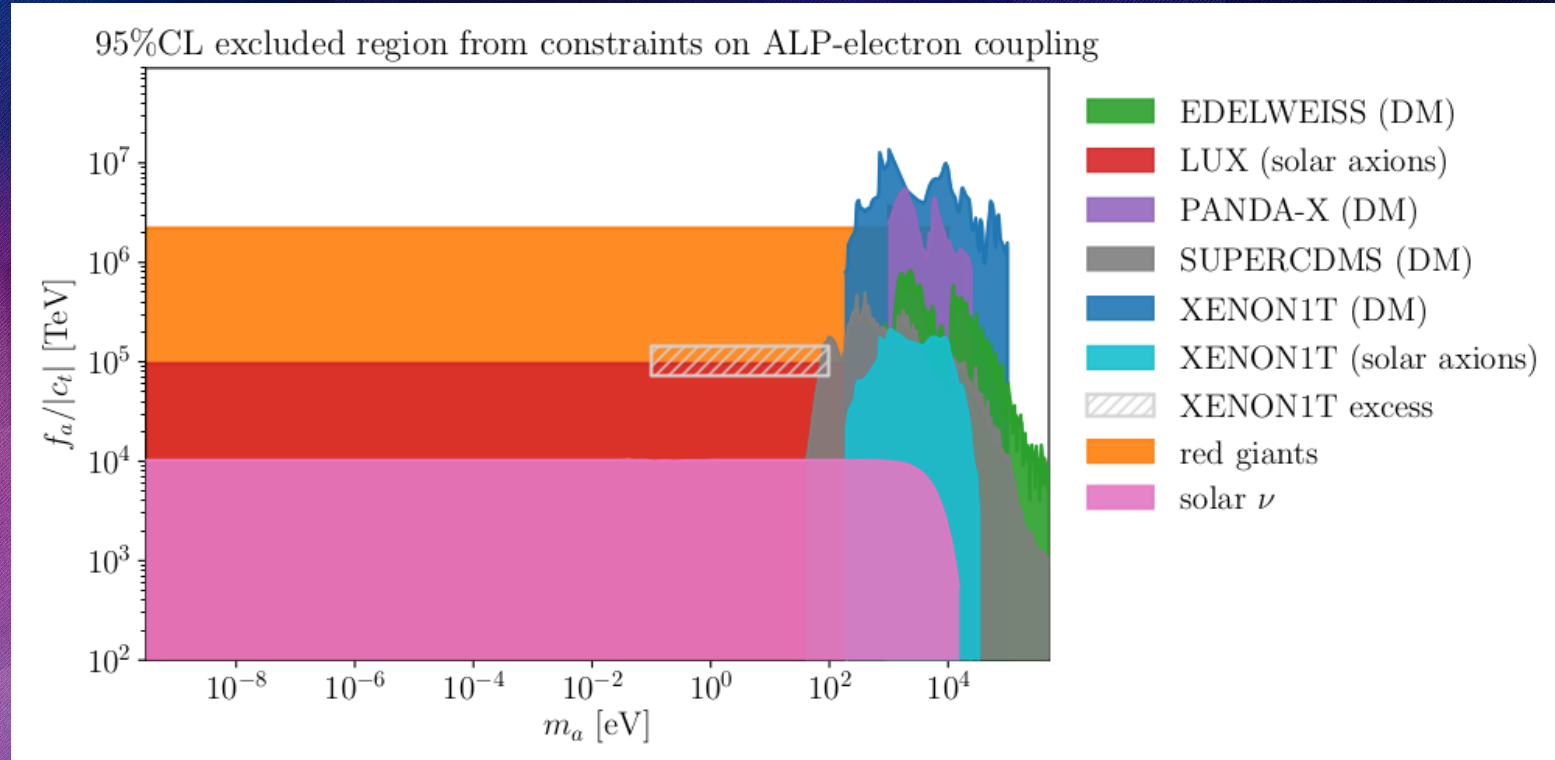
Below 10 GeV: Flavour Bounds



[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]

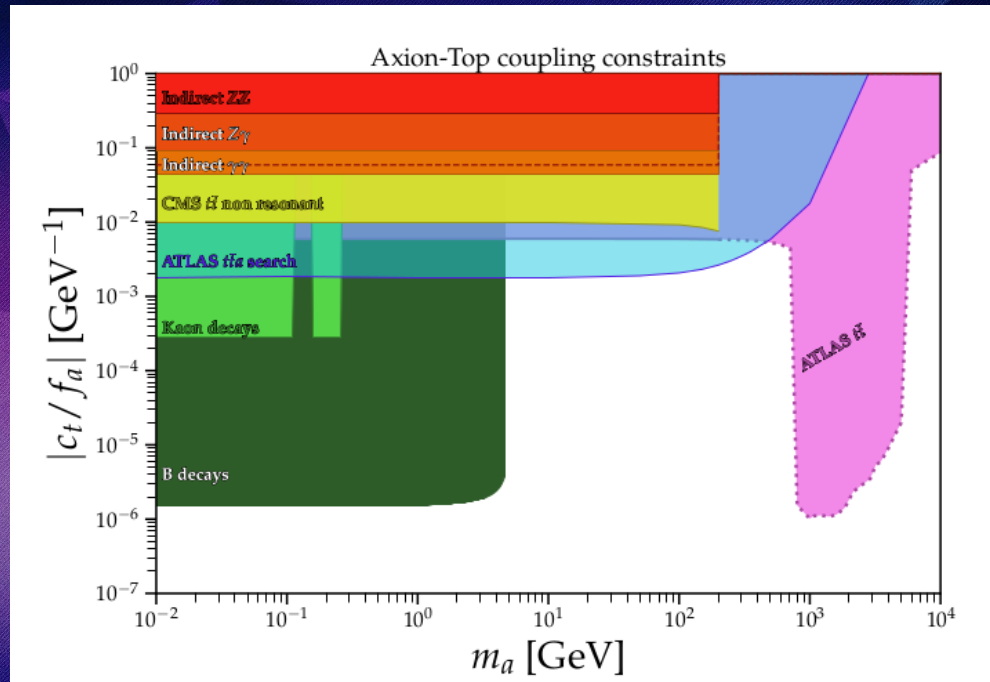
Below 1 MeV: Astro-Cosmological Bounds



[Bonilla, Brivio, Gavela, Sanz, 2107.11392]

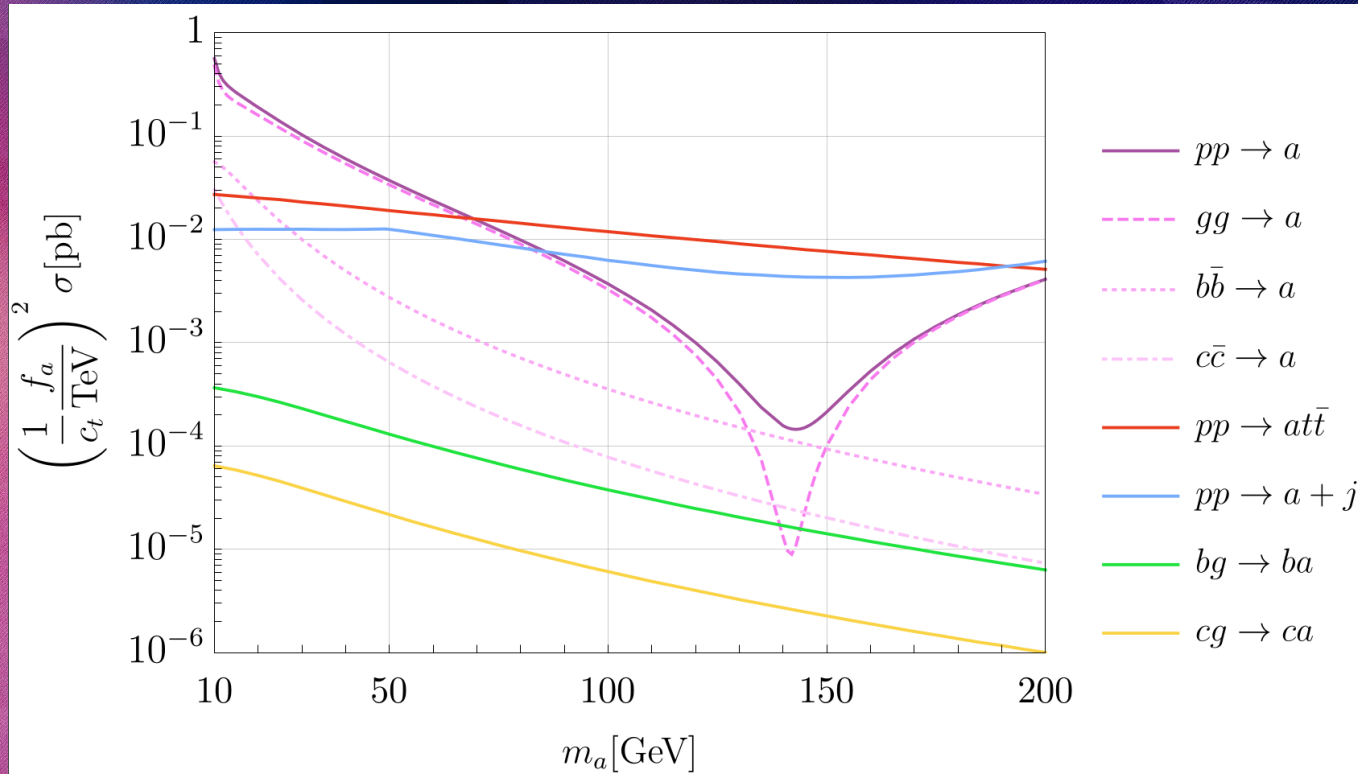
Above 200GeV axion mass

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



[Esser, Madigan, Sanz, Ubiali, 2303.17634]

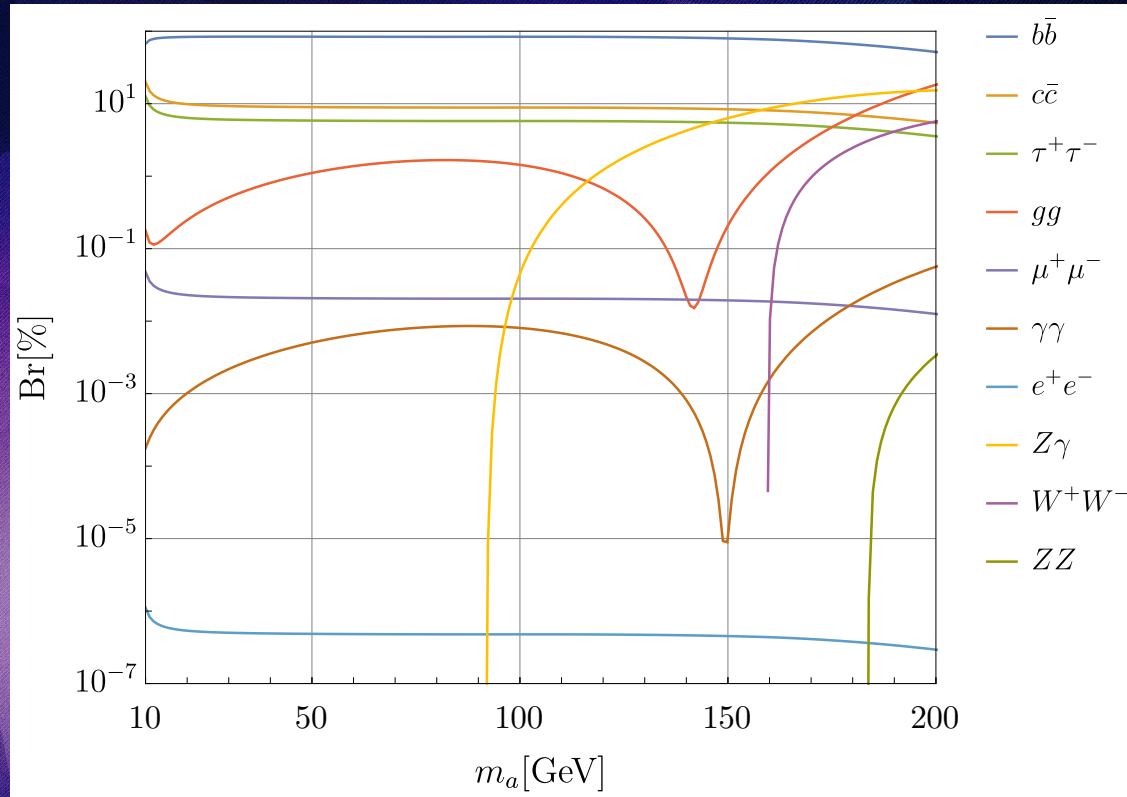
The Golden Region: 10-200 GeV Production



- Gluon-fusion requires 2-loop accuracy
- Jet associated production loop-induced
- Production in association with $t\bar{t}$ LO

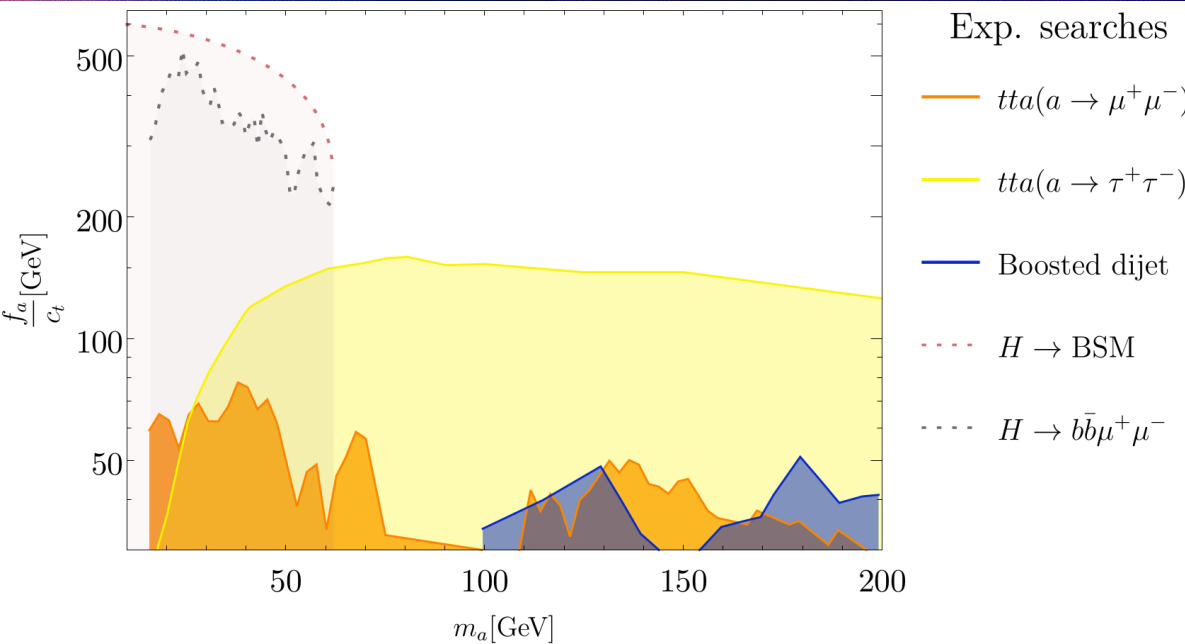
The Golden Region: 10-200 GeV

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

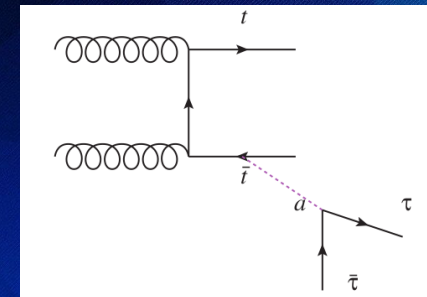
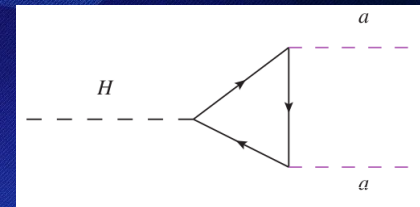
[ATLAS, 2211.04172, 2102.13405, ATLAS-CONF-2023-035]

- Resonant boosted $b\bar{b}$

[CMS, 1810.11822]

- $Z \rightarrow \text{BSM}$, $Z \rightarrow \gamma a(\tau\bar{\tau})$, $Z \rightarrow \gamma a(jj)$

LEP



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)

↓

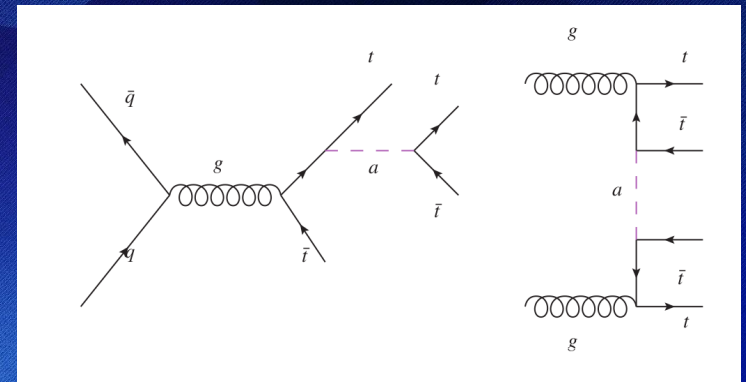
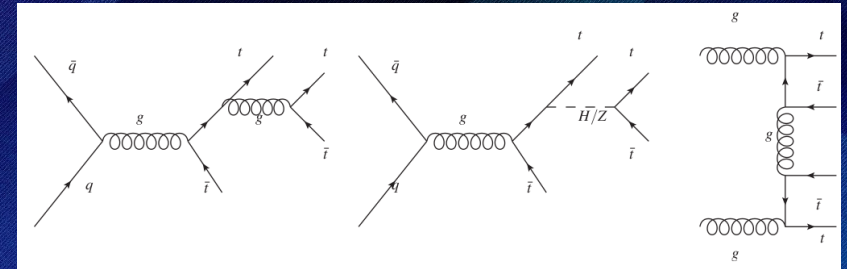
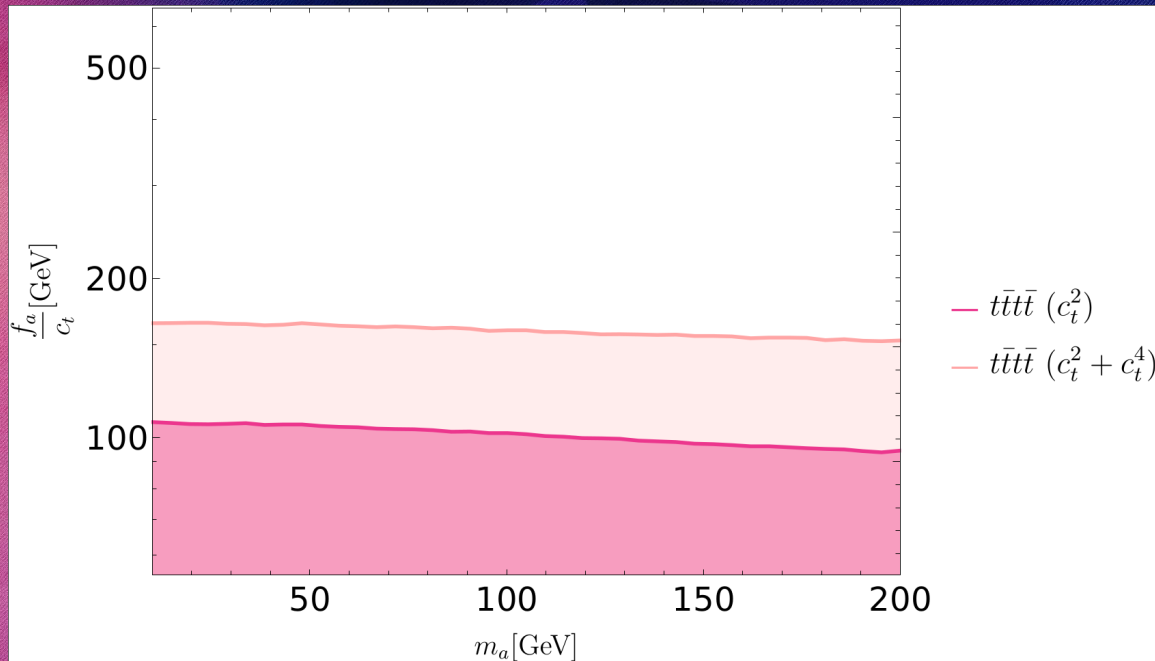
- Monojet + missing energy
- $t\bar{t}$ + missing energy

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

Four-top total cross section

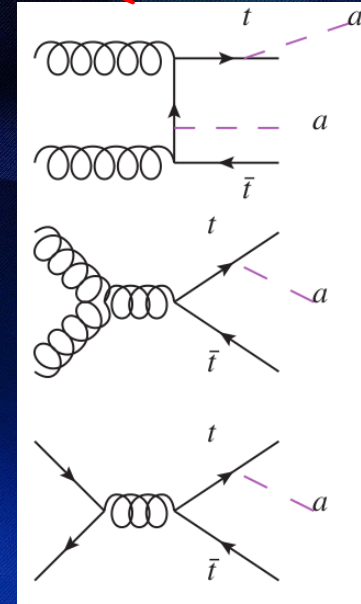
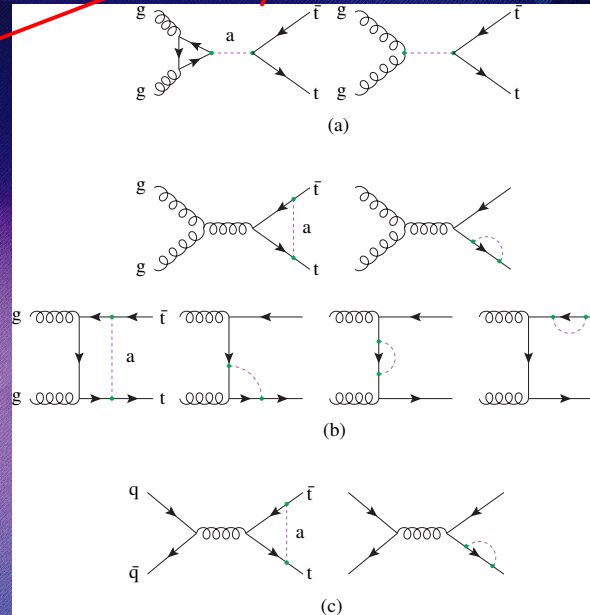
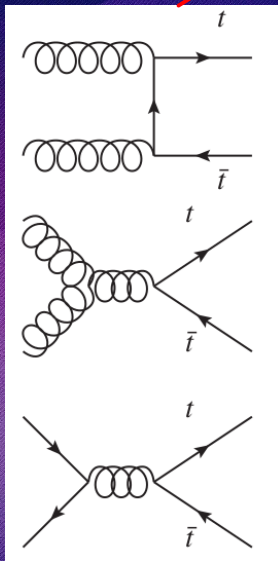
[ATLAS, 2303.15061]
 [ATLAS, 2106.11683]
 [CMS, 2305.13439]
 [CMS, 2303.03864]

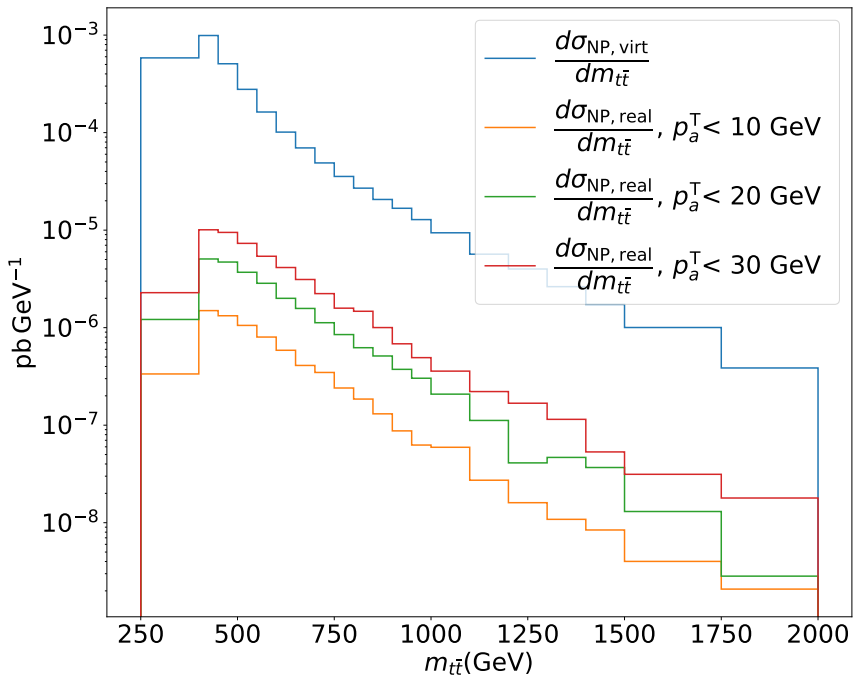
$$\left(\frac{c_t}{f_a}\right)^{2n} \alpha_S^m \alpha_{EW}^l \quad \text{with} \quad n + m + l = 4 \quad \text{and} \quad n \leq 2$$



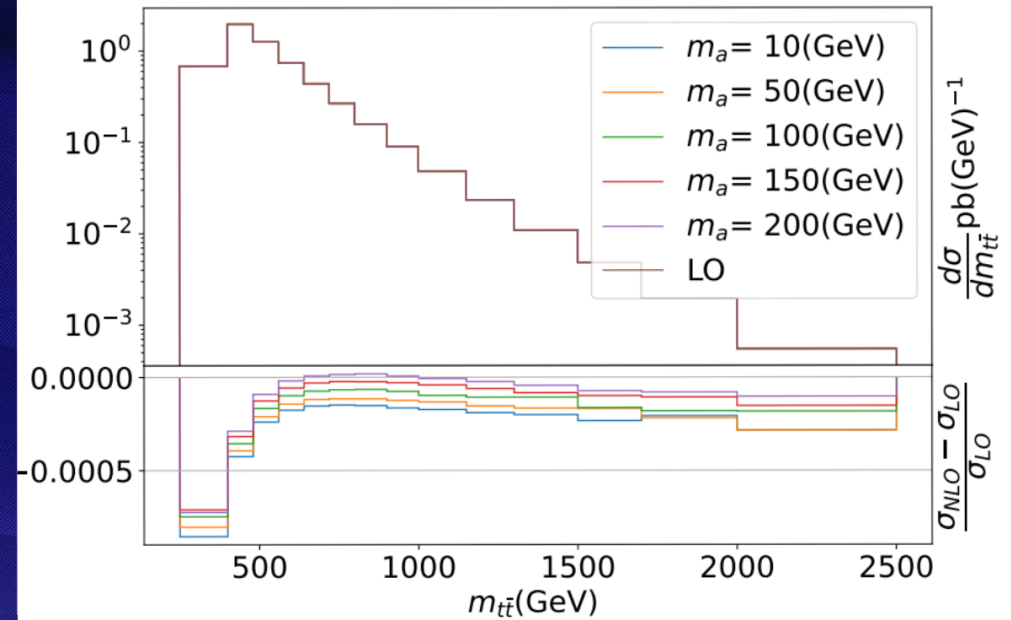
$t\bar{t}$ differential distributions

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





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



Big corrections near the threshold

Corrections weakly dependent on ALP mass

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

\sqrt{s}	Collab.	Channel	bins
8 TeV	ATLAS	Dilepton	6
8 TeV	ATLAS	ℓ -jets	7
8 TeV	CMS	Dilepton	6
8 TeV	CMS	ℓ -jets	7
13 TeV	ATLAS	ℓ -jets	9
13 TeV	CMS	Dilepton	7
13 TeV	CMS	ℓ -jets	10
13 TeV	CMS	ℓ -jets	15

[1607.07281]

[1511.04716]

[1505.04480]

[1505.04480]

[1908.07305]

[1811.06625]

[1803.08856]

[2108.02803]

p_t distributions

\sqrt{s}	Collab.	channel	bins
8 TeV	ATLAS	ℓ -jets	8
8 TeV	CMS	Dilepton	5
8 TeV	CMS	ℓ -jets	8
13 TeV	ATLAS	ℓ -jets	8
13 TeV	CMS	Dilepton	6
13 TeV	CMS	ℓ -jets	17

[1511.04716]

[1505.04480]

[1505.04480]

[1908.07305]

[1811.06625]

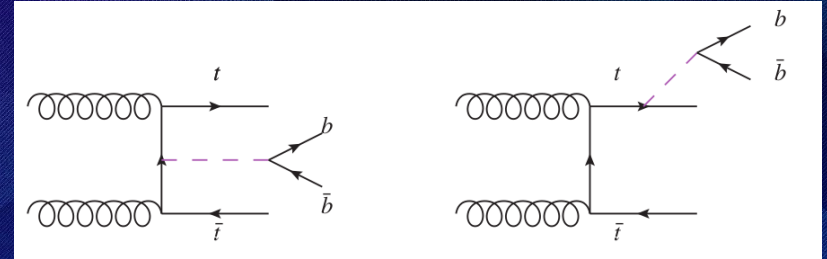
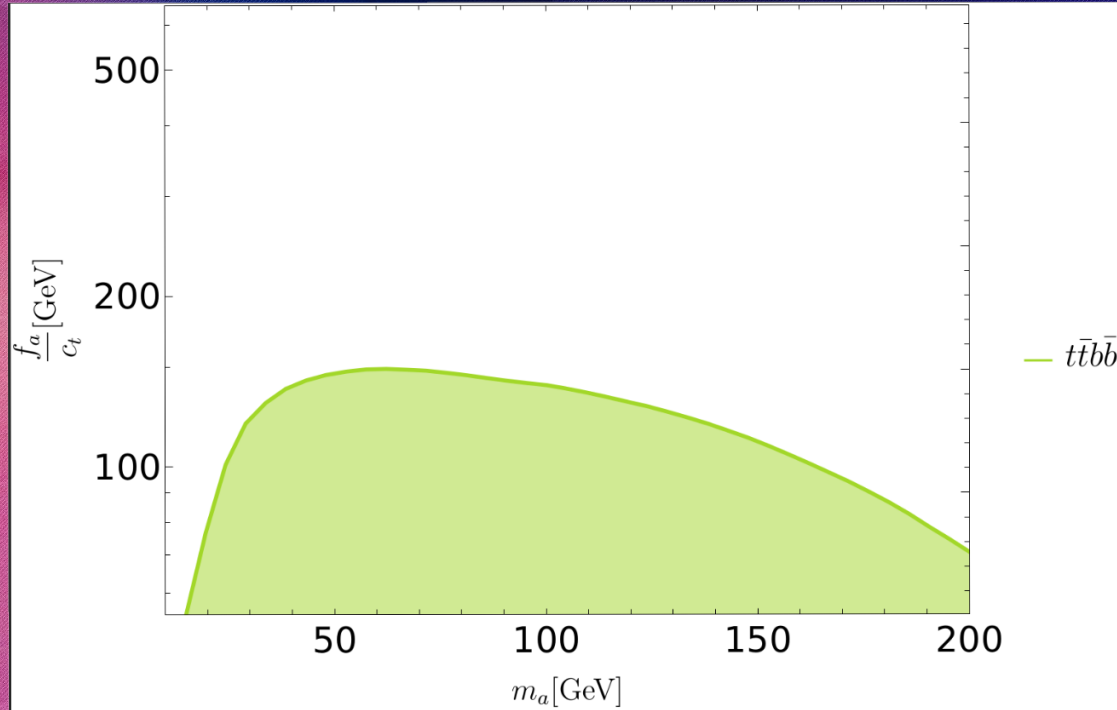
[2108.02803]

$$\chi^2(m_a, c_t/f_a) = (\vec{\mu}(m_a, c_t/f_a) - \vec{\mu}_{\text{obs.}}) \cdot \mathbf{V}^{-1} \cdot (\vec{\mu}(m_a, c_t/f_a) - \vec{\mu}_{\text{obs.}})$$

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]

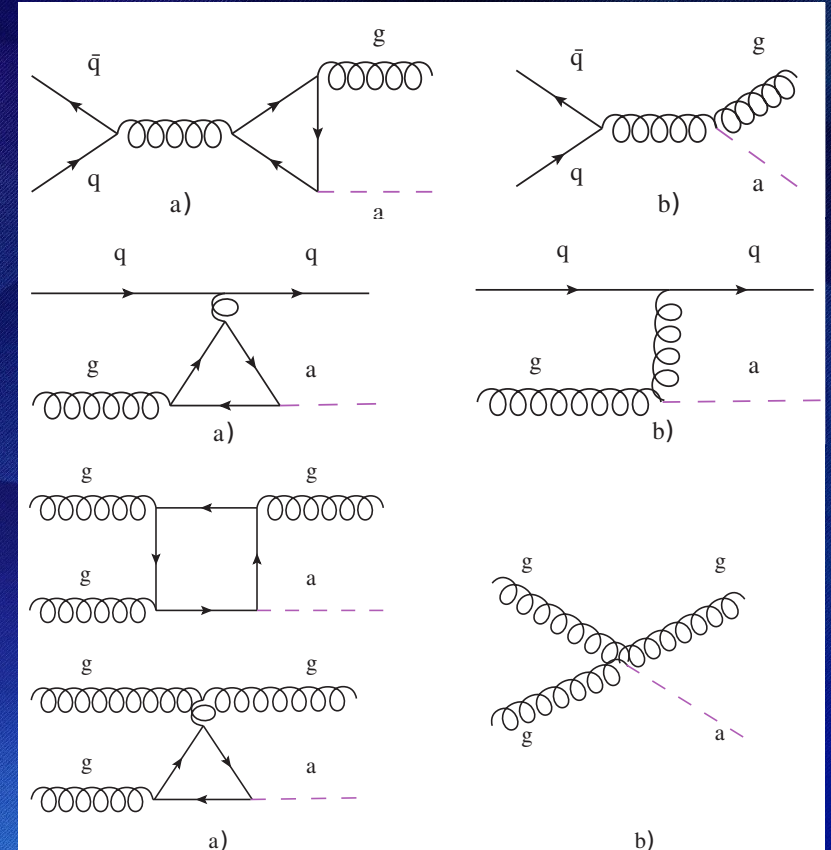
Exp.	Channel	$\mu_{t\bar{t}b\bar{b}} \pm \text{stat.} \pm \text{syst.}$	Ref.
CMS	dilepton	$1.36 \pm 0.10 \pm 0.34$	[63]
CMS	lepton+jets	$1.26 \pm 0.04 \pm 0.31$	[63]
ATLAS	dilepton ($e\mu$, 4b)	$1.75 \pm 0.05 \pm 0.56$	[61]
ATLAS	lepton+jets (4b)	$1.57 \pm 0.09 \pm 0.49$	[61]

Invisible ALP: monojet

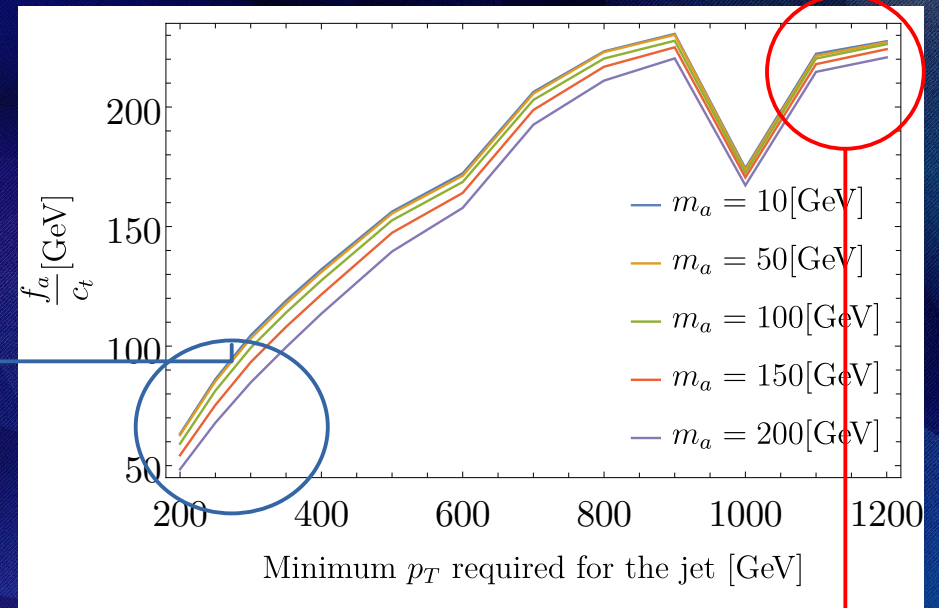
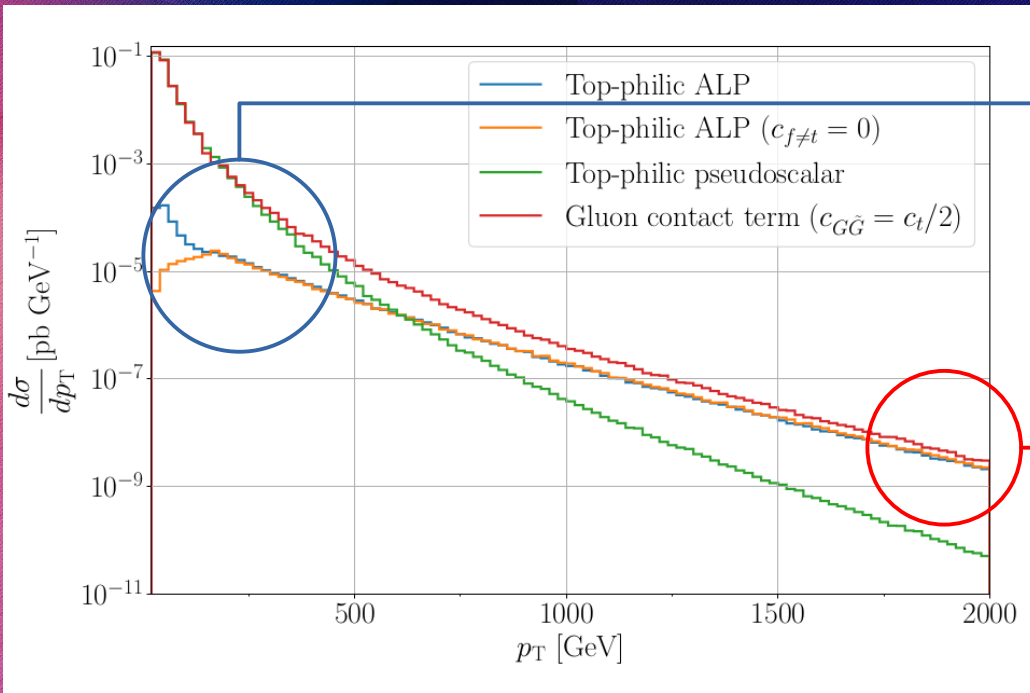
ALP can be invisible:

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

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



Invisible ALP: monojet



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

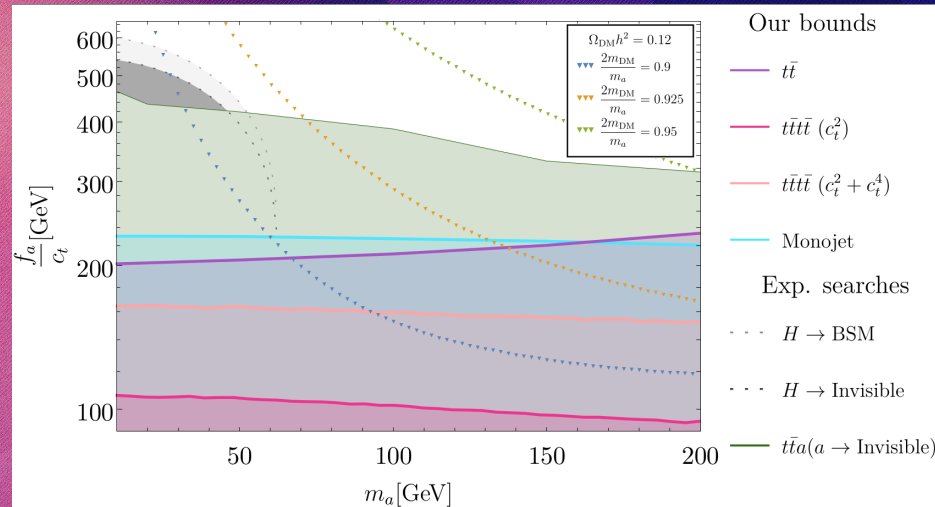
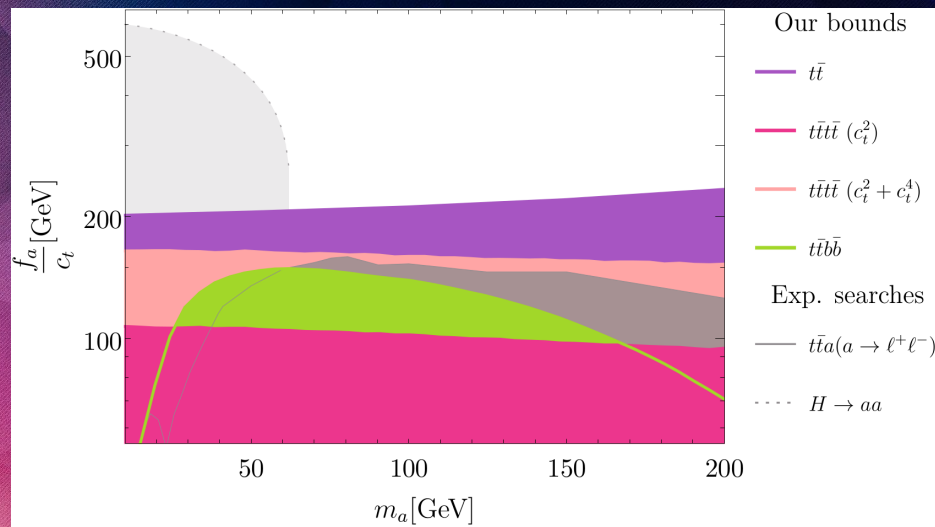
Visible Axion:

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

Invisible Axion:

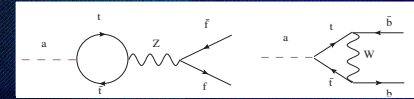
- At low masses Higgs decay gives strong bounds
- Monojet and $t\bar{t}$ are strong and same order
- $t\bar{t}$ + missing energy provides the best bound

[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

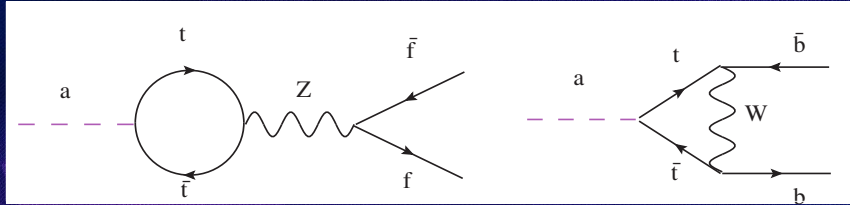


Extra

About top-philic ALP monogamy

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[Bauer, Neubert, Renner, Schnubel Thamm, 2012.12272,
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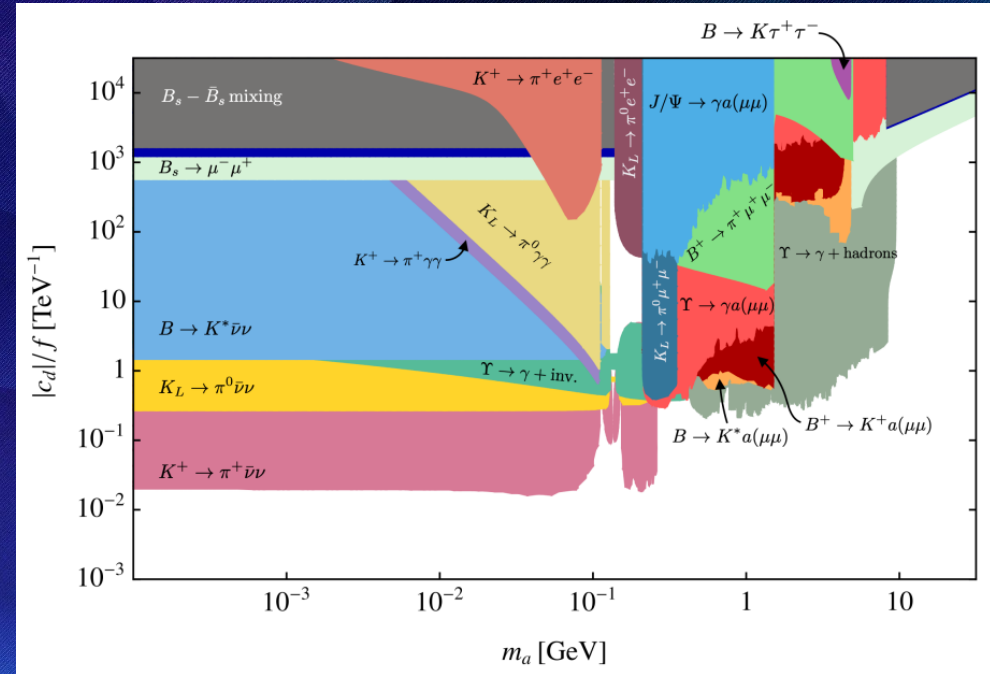
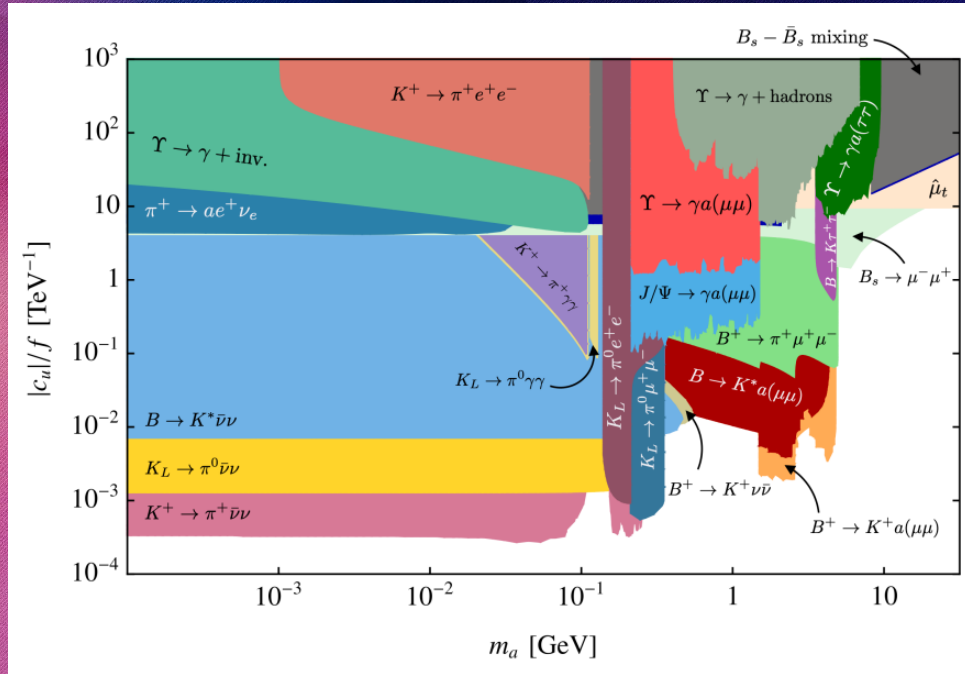


- Coupling sign depends on T_3^f
- UV scale Λ ($\Lambda \approx 1\text{TeV} - 4\pi\text{TeV}$)
- Correction up to $c_f \sim 5 - 10\% c_t$

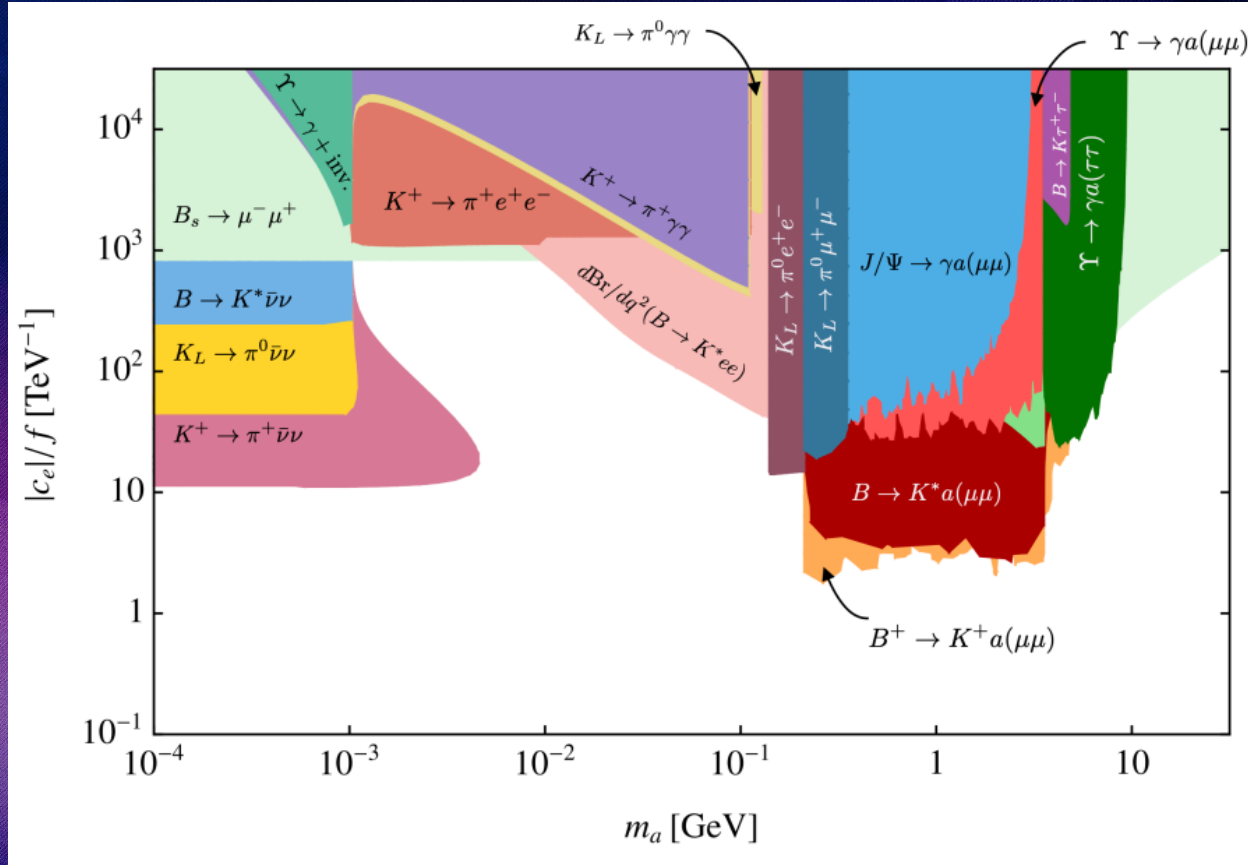
$$\mathcal{L}_{a,\text{int}} = \sum_f -ic_f \frac{m_f}{f_a} a \bar{\psi}_f \gamma_5 \psi_f + \sum_f \frac{c_f}{2} \frac{\alpha_S}{4\pi} \frac{a}{f_a} G\tilde{G} + \text{E.W. terms}$$

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

Up-like and Down-like Flavour bounds



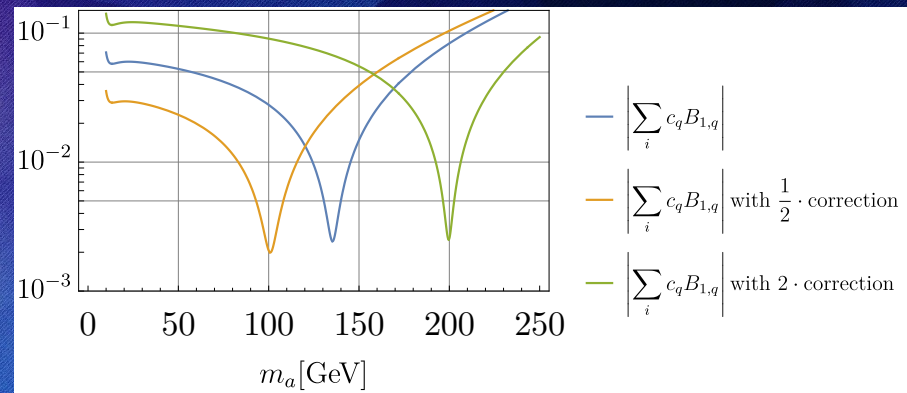
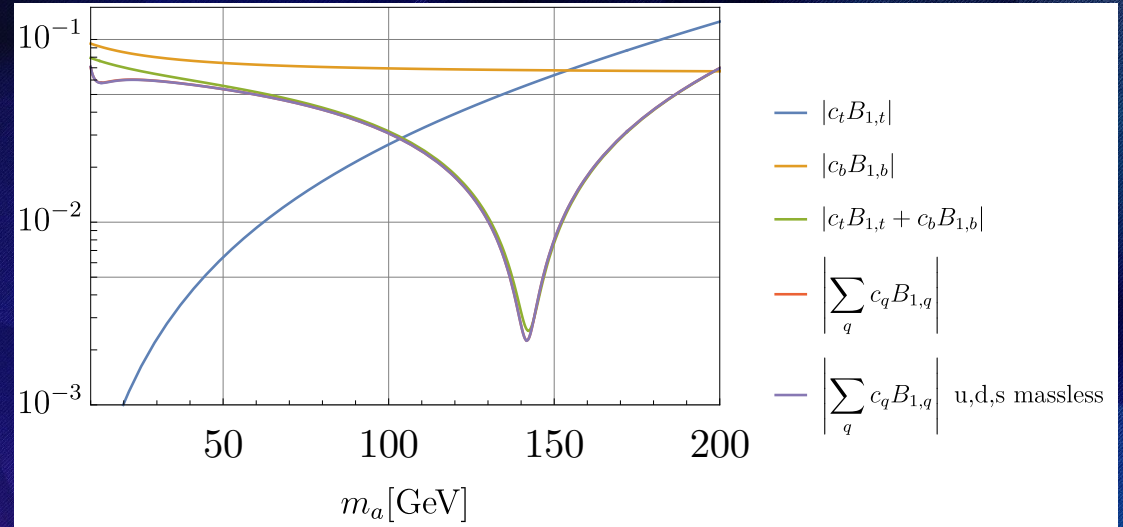
Down-like Leptons Flavour bounds



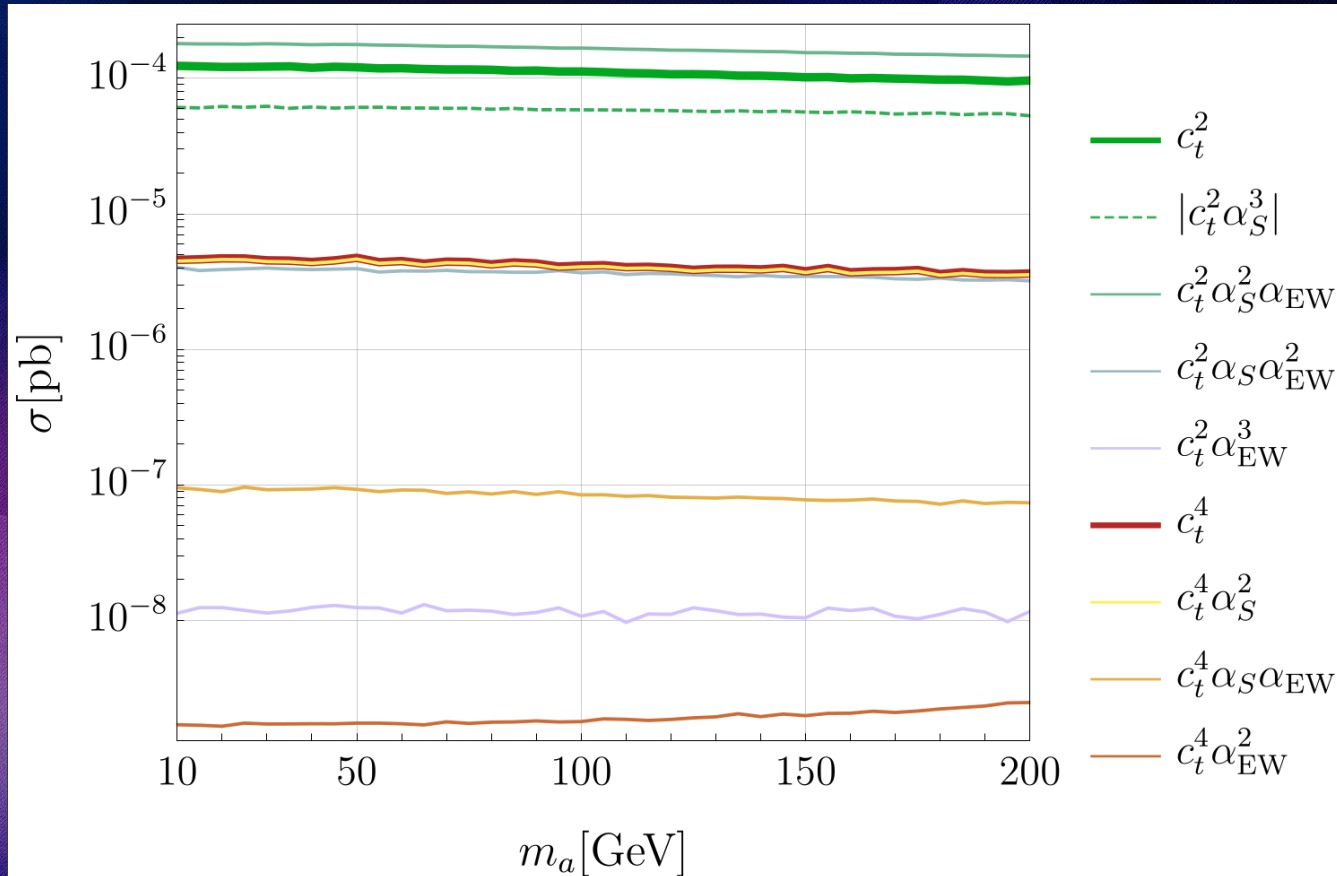
FULL QUARKS CONTRIBUTION TO DI-GLUON(PHOTON) DECAY

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

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



4 Top Contributions Breakdown



INVISIBLE ALP: DM SCENARIO

