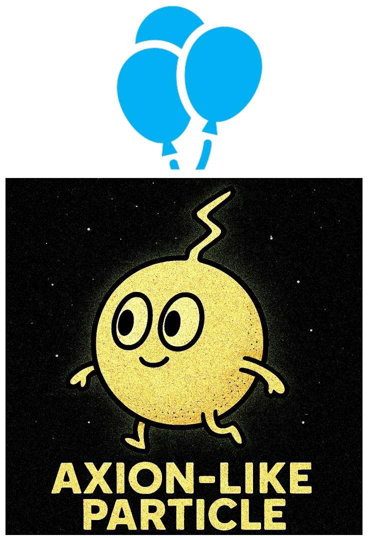
Collider searches for Light Axion-Like Particles in Top Quark Sector

Mojtaba Mohammadi Najafabadi
Institute for Research in Fundamental Sciences (IPM) and CERN EP

IRN Terascale@Montpellier (Nov 24-26)

Outlines



- Motivations and theoretical framework
- ALP Behaviours
- ALP Production at the LHC with Invisible Final States
- Probing ALP Parameter Space through $t\bar{t}$ + a and tW + a processes
- Interpretation using $t\bar{t}Z$ (Z → Invisible)
- Summary

Motivation – What are ALPs?

- Axion-Like Particles (ALPs) Pseudo–Goldstone bosons from the spontaneous breaking of global symmetries in many BSMs.
- The Lagrangian consists of all SM states + a single ALP field a
- The Lagrangian gauge-invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Derivative and anomalous couplings to SM particles:

$$\mathcal{L}_{ALP} = \mathcal{L}_{SM} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \left(\frac{\partial_\mu a}{f_a}\right) \times SM^\mu + \left(\frac{a}{f_a}\right) \times V^{\mu\nu}\tilde{V}_{\mu\nu}$$

Derivative couplings from the Goldstone nature. Coupling grows with momentum.

Symmetry breaking scale or ALP decay constant

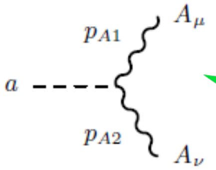
V = *G,W,B*. Anomalous coupling-like interactions to gauge bosons (gg, γγ, Zγ, WW, BB)

- Light ALP protects approximately the shift symmetry: ***a* → *a* + *c***
- Predicted by many BSMs : axion (PQ symmetry), majoron (dynamical neutrino masses, Lepton number), string theory, flavon (flavour symmetry), extra dimensions, etc...
- ALPs can solve (i) the strong CP problem, (ii) serve as Dark Matter candidate, (iii) solve the observed matter-antimatter

Axion-Like Particles couplings to SM

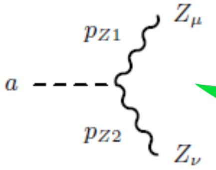
Eur.Phys.J.C 77 (2017) 8, 572

Vertices:



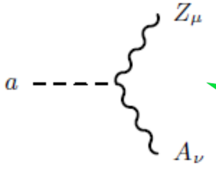
$$\delta\mathcal{L}_a \supset -\frac{1}{4}\, g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{a\gamma\gamma} = \frac{4}{f_a}\,(c_{\tilde{B}}\, cos^2\theta_w + c_{\tilde{W}}\, sin^2\theta_w)$$



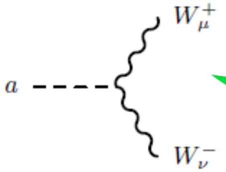
$$\delta\mathcal{L}_a \supset -\frac{1}{4}\, g_{aZZ}\, a\, Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$g_{aZZ} = \frac{4}{f_a}\,(c_{\tilde{B}}\, sin^2\theta_w + c_{\tilde{W}}\, cos^2\theta_w)$$



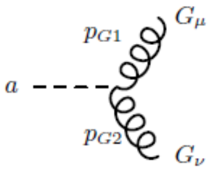
$$\delta\mathcal{L}_a \supset -\frac{1}{4}\, g_{aZ\gamma}\, a\, Z_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{aZ\gamma} = \frac{2}{f_a}\, sin2\theta_W\,(c_{\tilde{W}} - c_{\tilde{B}})$$



$$\delta\mathcal{L}_a \supset -\frac{1}{4}\, g_{aWW}\, a\, W_{\mu\nu}\widetilde{W}^{\mu\nu}$$

$$g_{aWW} = \frac{4\, c_{\tilde{W}}}{f_a}$$



$$\delta\mathcal{L}_a \supset -\frac{1}{4}\, g_{agg}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$g_{agg} = \frac{4\, c_{\tilde{G}}}{f_a}$$

The amplitude scales as:

$$\mathcal{M} \propto \frac{g_{aVV}}{f_a} \times (p_1.p_2)\varepsilon_1\varepsilon_2$$

grows with the momentum transfer.

At high-energies , the cross section increases with energy (until EFT validity breaks down).

Axion-Like Particles couplings to SM

The ALP couples derivatively to the top quark axial current:
This form is shift-symmetric, i.e. invariant under $a \rightarrow a + \text{constant}$, up to total derivatives.
It reflects the Nambu–Goldstone nature of the ALP.

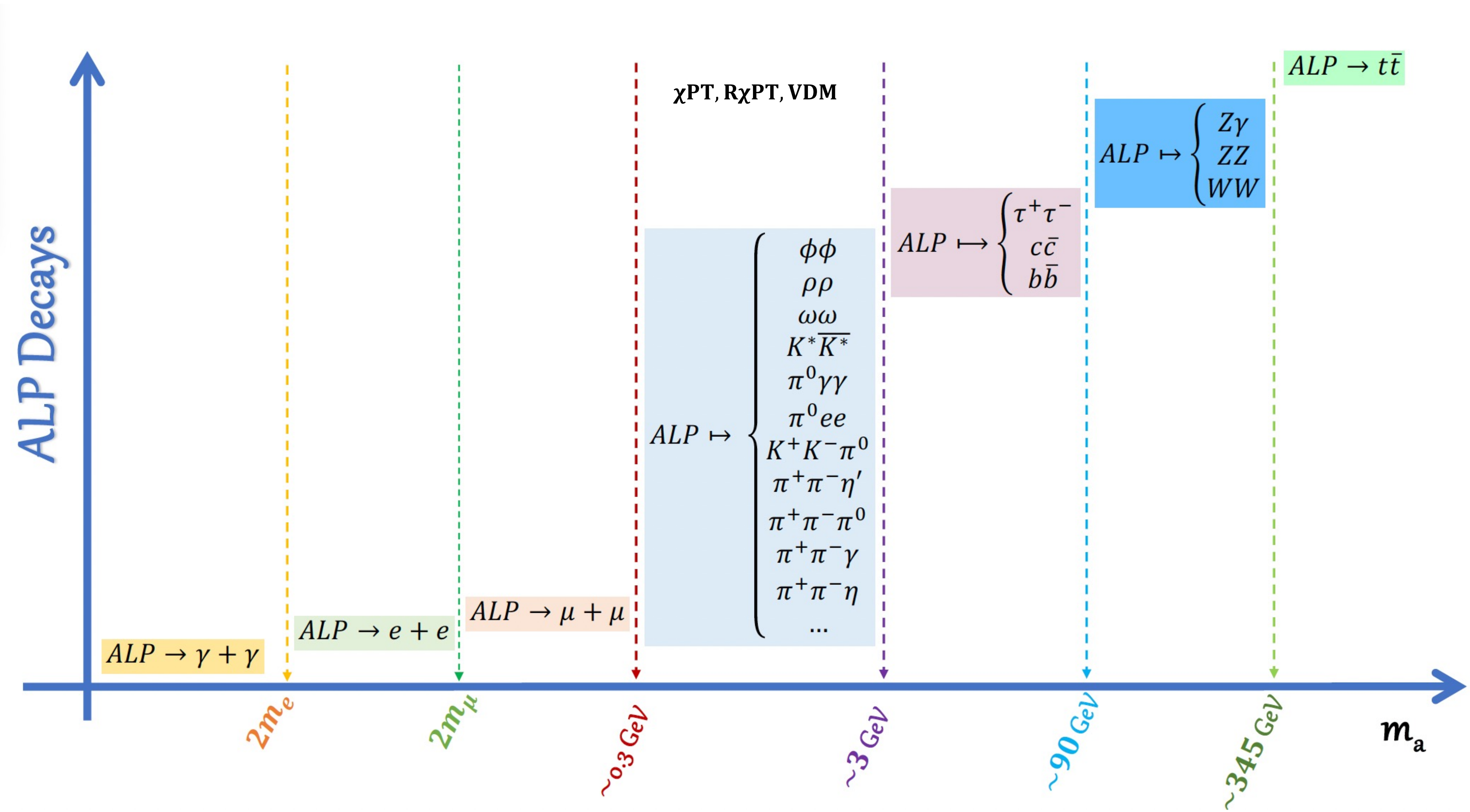
$$\mathcal{L} = c_t \frac{\partial_\mu a}{2 f_a} (\bar{t}\gamma^\mu \gamma^5 t) \,,$$

Apply the equation of motion (EOM)

$$\mathcal{L} = -i\, c_t \frac{m_t a}{2 f_a} (\bar{t}\gamma^5 t)$$

- The derivative coupling is equivalent (on-shell) to a pseudoscalar Yukawa interaction with a strength proportional to the ratio of top quark mass to the global symmetry-breaking scale.
- This is analogous to how the Higgs field couples proportionally to mass but for the ALP, the interaction is pseudoscalar and derivative in origin.
- The top sector dominates ALP production and loop-induced couplings (e.g. , $a\gamma\gamma$, agg). As a result, keeping only the top coupling is often sufficient when computing collider observables.

ALP decay modes



ALP Behaviours: Parameter Space and Strategy

The phenomenology of ALPs at the LHC depends crucially on their mass and decay width, or equivalently, their lifetime or proper decay length. Depending on these parameters, ALPs can give rise to very different experimental signatures.

Small g → invisible; intermediate g → long-lived; large g → prompt; very large g or very heavy m_a → off-shell.

Behaviour	Proper Decay Length $c\tau_a$	Typical m_a Range	Dominant Decay Modes / Signature
Collider-stable (invisible)	> $L_{det.}$ ~ O(10) m	1 MeV – few GeV (or any mass for ultra-small couplings)	None (ALP escapes); MET + jets/leptons/photons
Long-lived (displaced)	few mm to L_{det}	1 MeV – O(100 GeV)	$\gamma\gamma$, e^+e^-, $\mu^+\mu^-$; displaced vertex/delayed. Macroscopic lifetime, they can produce displaced vertices. For example, in the inner tracker or muon system. experimentally challenging.
Resonant (prompt)	< 0.1 mm	few MeV – TeV	Prompt resonances depending on the mass: $\gamma\gamma$, e^+e^-, hadronic, $c\bar{c}$, $b\bar{b}$, $\tau^+\tau^-$, WW, ZZ, Zγ, $t\bar{t}$. Appear as resonances in various visible final states
Virtual (off-shell)	$\ll 10^{-15}$ m	$\Gamma \approx m_a$ or $m_a \gg 1$ TeV, Heavy (multi-TeV) or strongly coupled	EFT effects (no on-shell)

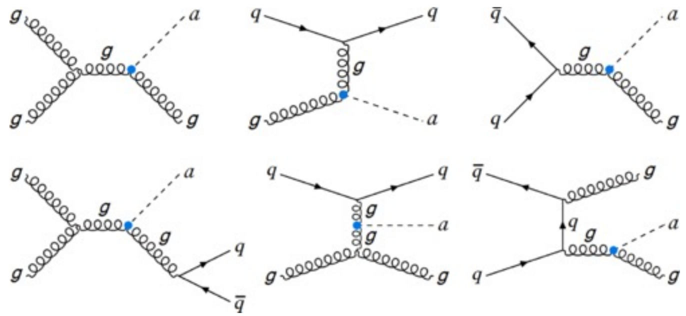
Among these phenomenological regimes this work targets
the collider-stable ALP case, characterized by a decay length $c\tau_a > L_{det}$ and an experimental signature of MET + jets/leptons/photons.

ALP Production at the LHC with Invisible Final States (ALP → ME)

The LHC provides a unique environment to probe ALP couplings due to its high center-of-mass energy and large parton luminosities. In particular:

Couplings to Gluons ($c_{\tilde{G}}$)

-Gluon fusion: mainly though gga : gg → a + j, gg → a + jj, gg → a + ttbar, gq → a + j + γ, …



- Highest cross section at the LHC; monojet channel provides strongest limits; sensitive to low m_a .

Couplings to W boson ($c_{\tilde{W}}$)

Associated Production: pp → W + a; pp → W^+W^- + a; VBF: qq → qq + a –
Final States: - W(lν) + MET and 2 forward jets + MET

- VBF topology (large rapidity gap) helps suppress backgrounds.

ALP Production at the LHC with Invisible Final States (ALP → MET)

Couplings to Photons ($g_{a\gamma\gamma}: c_{\tilde{B}}\ and\ c_{\tilde{W}}$)

→ Accessible in processes like $pp \longrightarrow \gamma + a$, … Mono-photon signature

Photon p_T spectrum and angular distributions can be modelled precisely → The amplitude grows with energy (E^2/f_a^2), so the high-p_T tail is sensitive to EFT structure. Ideal for fitting the cutoff scale f_a and the relative coefficients.

Couplings to Z-bosons ($g_{aZZ}: c_{\tilde{B}}\ and\ c_{\tilde{W}}$)

pp → Z + a ⁓ pp → ZZ + a (rare), VBF: qq → qq + a , Final state: Z ($l^+ + l^-$) + MET ⁓ ZZ + MET

Very clean but small rates; suitable for high-luminosity or future collider stages.

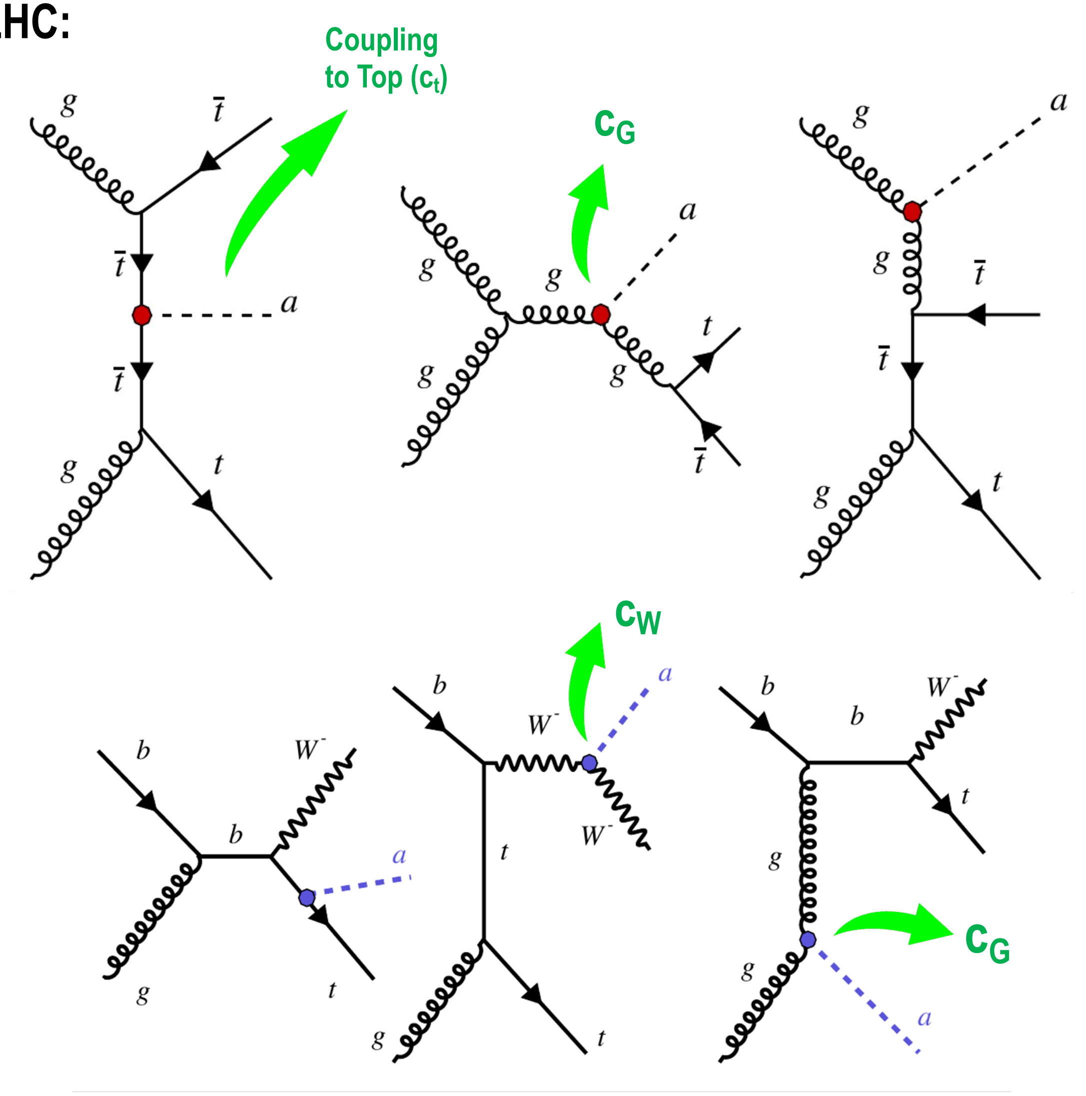
ALP Production Channels Associated with Top quark

Two production channels at the LHC:

-Phys.Rev.D 110 (2024) 5, 055026 (Y. Hosseini, MMN)
-Phys. Rev. D 100, 015016 (2019) (J. Ebadi, et al)
-Special Issue Top Quark at the New Physics Frontier Universe 8 (2022) 6, 301 (Y. Hosseini, MMN)

– $t\bar{t}$ + a ($t\bar{t}$ + MET)

– ALP Production in the tW + a (tW + MET)



Physical Review D 110, 055026 (2024)

Particularly well-suited to LHC studies due to the large $t\bar{t}$ production rate & the top's large Yukawa coupling.

Cross section enhanced by m_t/f_a; one of the most sensitive probes; enables direct connection to top-ALP effective operators.

ALP Behaviours: Decay Probability

Focus of this work We consider the collider-stable ALP scenario (ALP → invisible, MET signature).

ALP Decay Probability in the Detector needs to be considered:

$$P_{decay} = 1 - e^{-L_{Det}^{T}/L_a}$$

Where L_{Det}^{T} is the transverse distance of the detector component and L_a is the decay length of the ALP perpendicular to the beam axis, which has the following form:

$$L_a = \gamma\beta \times \tau_a \times \sin\theta = \frac{|\vec{p_a}|}{m_a} \times \tau_a \times \sin\theta \text{ with } \tau_a = 1/\Gamma_a^{total}$$

For $m_a < 2m_e$: the only open decay mode is $a \to \gamma + \gamma$ therefore: $\Gamma_a^{total} = \Gamma_{a\mapsto\gamma\gamma} = \left(\frac{m_a^3}{4\pi}\right) \times \left(\frac{c_{\gamma\gamma}}{f_a}\right)^2$

If we set:

m_a = 1 MeV and $\frac{c_{\gamma\gamma}}{f_a} < 10^{-12}\ \text{GeV}^{-1}$ →→→ $L_a \gtrsim (2.3 \times |p_a|) \times 10^{21}$ m.

From Supernova SN1987a

ALP Behaviours: Decay Probability

With $\frac{c_{\gamma\gamma}}{f_a} < 10^{-5}\ \mathrm{GeV}^{-1}$ from Beam Dump Experiment
and $\frac{c_{ee}}{f_a} < 10^{-13}\ \mathrm{GeV}^{-1}$ from Red Giant.

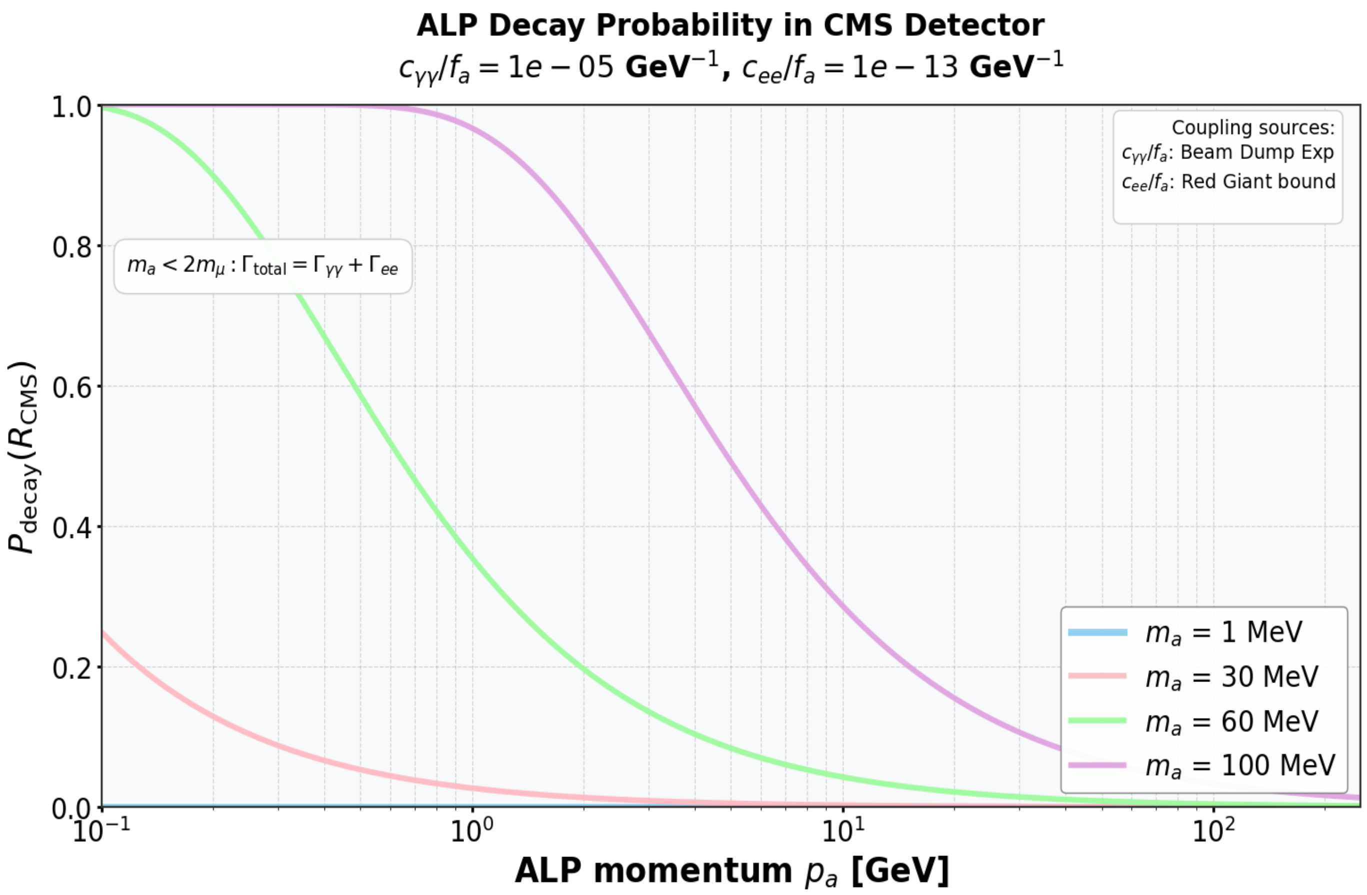
Transition from Collider Stable to Long-lived and Prompt.

-Lower mass ALPs have higher decay probabilities at lower momenta.

-Higher mass ALPs need more momentum to achieve significant decay probabilities.

-The 1 MeV ALP reaches near-unity probability quickly due to its longer proper lifetime.

-The 100 MeV ALP requires much higher momenta for detectable decays.



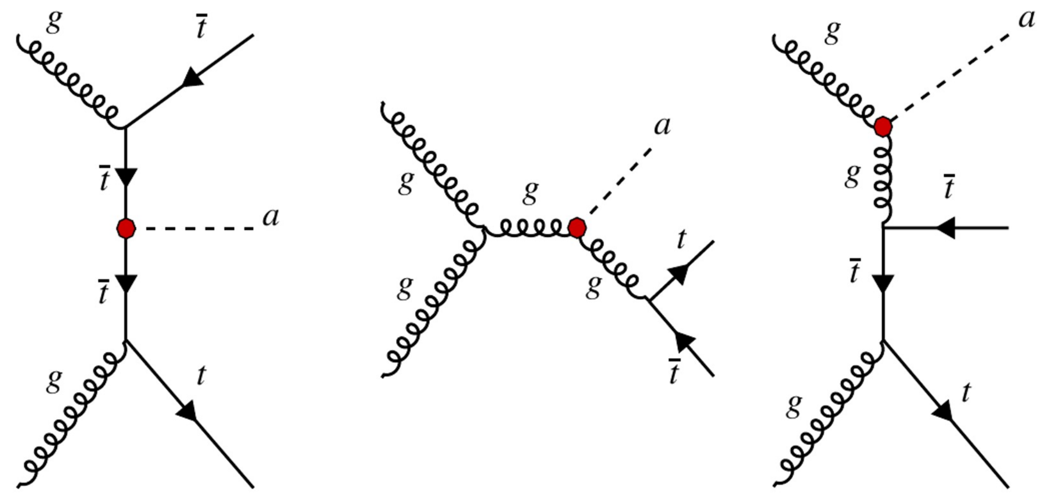
The electron coupling g_{aee} is now a crucial parameter that significantly affects the decay probabilities for ALP masses above ~ 1 MeV.

The 100 MeV ALP:
- is prompt/LLP for soft ALPs below 1-2 GeV
- becomes long-lived for 5–10 GeV
- becomes MET-like / stable above ~ 100 GeV

$t\bar{t}$ + a production → $t\bar{t}$ + MET

- This production channel is highly sensitive to the ALP couplings to gluons (c_G) and top quark (c_t).

- We probe collider stable region--> $t\bar{t}$ + a has a similar signature as SM $t\bar{t}$ and $t\bar{t}$ + Z (Z→vv)
- In $t\bar{t}$ + a production, the dominant initial states are:
  – quark–antiquark annihilation, and
  – gluon–gluon fusion.
  – gg dominates: L_gg >> L_qqbar at LHC energies.



- Since the ALP is invisible, MET ≈ $p_{T,a}$, the parametric behaviour of $d\hat{\sigma}/dp_{T,a}$ determines the MET spectrum in $t\bar{t}$ + a events.
  The differential cross section scaling:

$$\begin{cases} Low\ -p_{T,a}\ (\ll m_t): \dfrac{d\sigma}{dp_{T,a}} \propto \dfrac{1}{p_{T,a}} \\ High - p_{T,a}(\gg m_t): \dfrac{d\sigma}{dp_{T,a}} \propto \dfrac{1}{p^3{}_{T,a}} \\ \textit{Coupling Dependence}: \\ A\,(\dfrac{c_G}{f_a})^2 + B\,(\dfrac{c_t}{f_a})^2 + C\,\dfrac{c_t c_G}{f^2{}_a} \end{cases}$$

At high-energy:
-Low-pT (MET) region: the rate scales as $1/p_{T,a}$, producing an enhanced rate of soft ALPs (soft/MET-enhanced region).
-High-pT (MET) region: the cross section falls like $1/p^3_{T,a}$, strongly suppressing the production of energetic ALPs (hard/MET-suppressed region).

A >> B due to large gluon PDF and limited phase space for ALP emmission from top

Reinterpreting CMS Semileptonic $t\bar{t}$ + MET to Constrain $t\bar{t}$ + a

- **To obtain upper limits on the $t\bar{t}$ + a production rate, we implement the same event selection criteria used by the CMS semileptonic $t\bar{t}$ + MET search.**

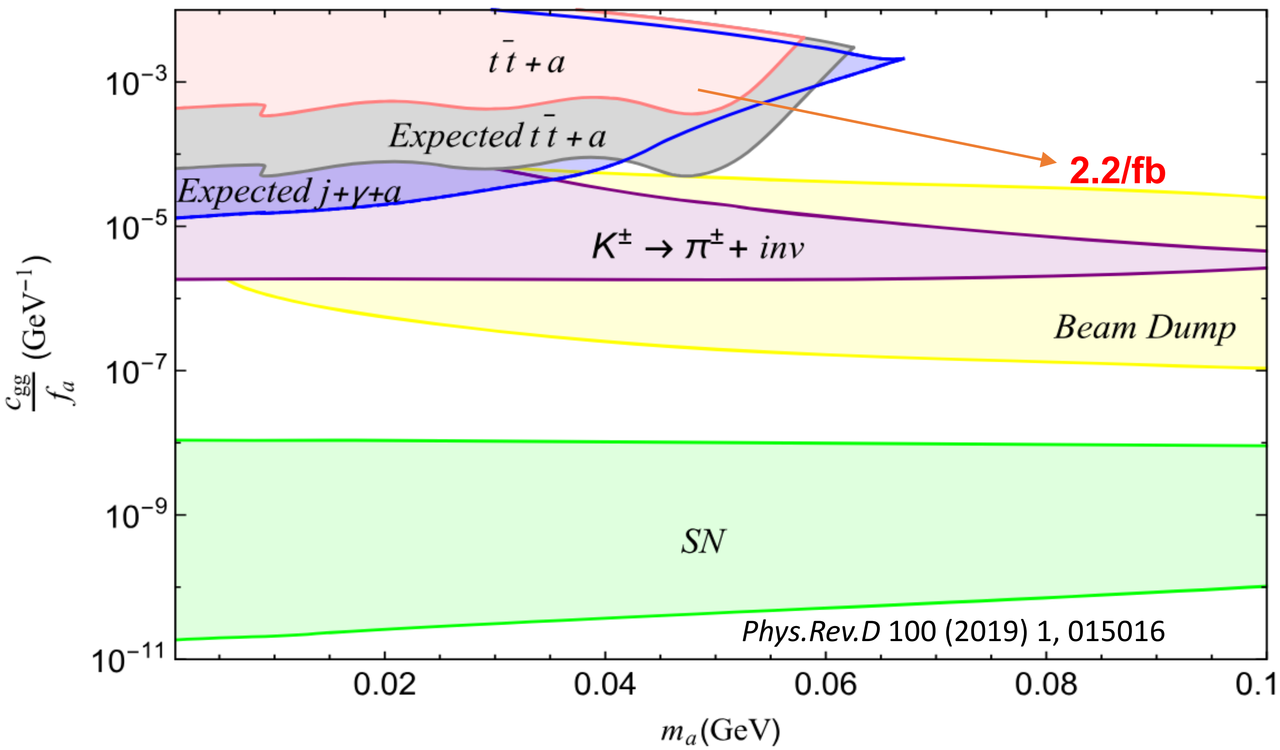
- **By applying this selection to our signal simulation and comparing with the CMS background expectations, we extract constraints on the ALP parameter space.**

Event Selections:

- Exactly one isolated charged lepton (electron or muon) with $p_T \geq 30$ GeV and $|\eta| \leq 2.5$,
- Events containing additional charged leptons with $p_T \geq 10$ GeV are rejected,
- At least three jets with $p_T \geq 30$ GeV and $|\eta| \leq 2.5$, with one being identified as a b-jet,
- **Missing transverse momentum greater than 160 GeV,**
- The transverse mass must exceed 160 GeV,
- The magnitude of the vector sum of all jets with $p_T \geq 20$ GeV and $|\eta| \leq 5.0$, HT , is required to be larger than 120 GeV,
- The M_{T2}^W must be greater than 200 GeV.

Eur. Phys. J. C (2017) 77:845

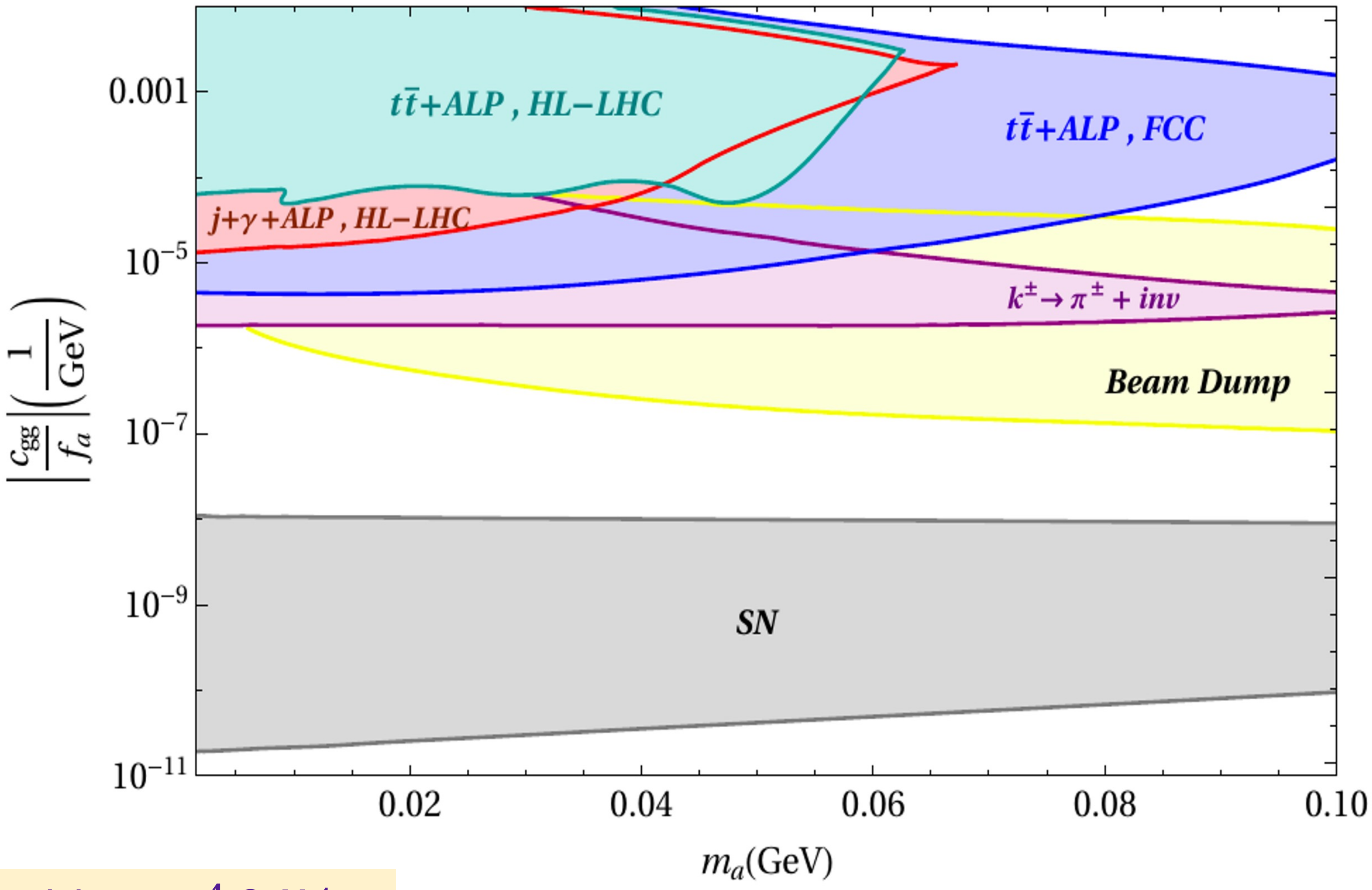
The current and projected constraints on the ALP-gluon coupling c_G/f_a as a function of the ALP mass m_a, compared with a variety of astrophysical, beam-dump, and flavour bounds.



- **Our recast of the CMS semileptonic $t\bar{t}$ + MET search yields new limits on the ALP–gluon coupling c_G/fa, excluding values around 10^{-3}–10^{-4} GeV^{-1} for ALP masses below 100 MeV.**
- **HL-LHC covers the intermediate coupling region between LHC collider limits and beam-dump constraints.**

$t\bar{t}$ + MET to Constrain $t\bar{t}$ + a @ FCC-hh

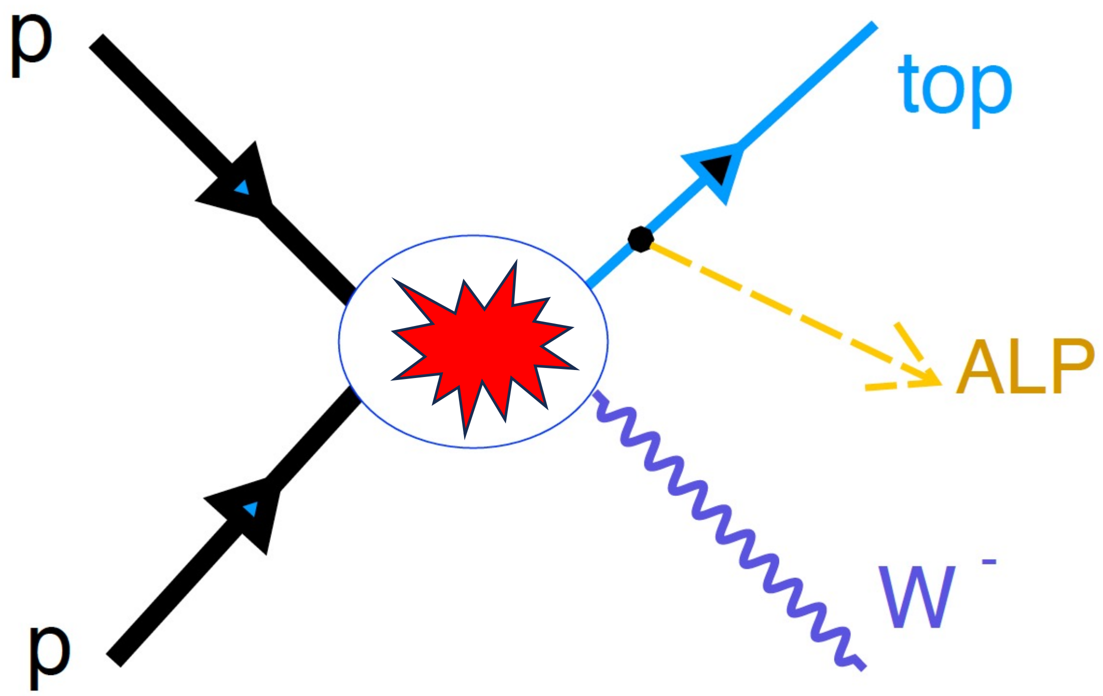
- At FCC-hh, hard ALP radiation becomes much more probable due to higher center-of-mass energy → strong sensitivity in the high-MET tail.
- The $1/p^3_{T,a}$ suppression is mitigated by the vastly increased phase space at FCC.
- **The FCC-hh analysis shows that a 100 TeV collider can probe ALP–gluon couplings down to 10^{-6} GeV^{-1}, improving upon the HL-LHC reach by over an order of magnitude.**
- **FCC-hh covers the region between HL-LHC and beam-dump constraints, providing the most sensitive probe of strongly coupled light ALPs.**



Upper limits on c_t/f_a for m_a = 1 MeV is found to be 1.1×10^{-4} GeV^{-1}

Special Issue Top Quark at the New Physics Frontier Universe 8 (2022) 6, 301

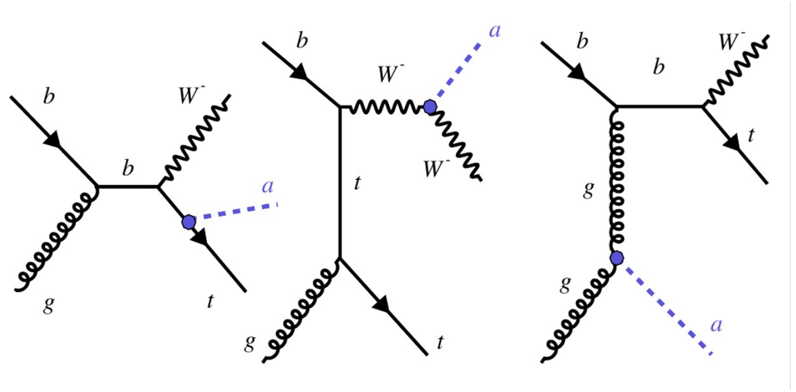
ALP Production in the tW + a Channel



ALP in the tW + a Channel: Probing ALP Couplings to Top, W, and Gluons

Physical Review D 110, 055026 (2024)

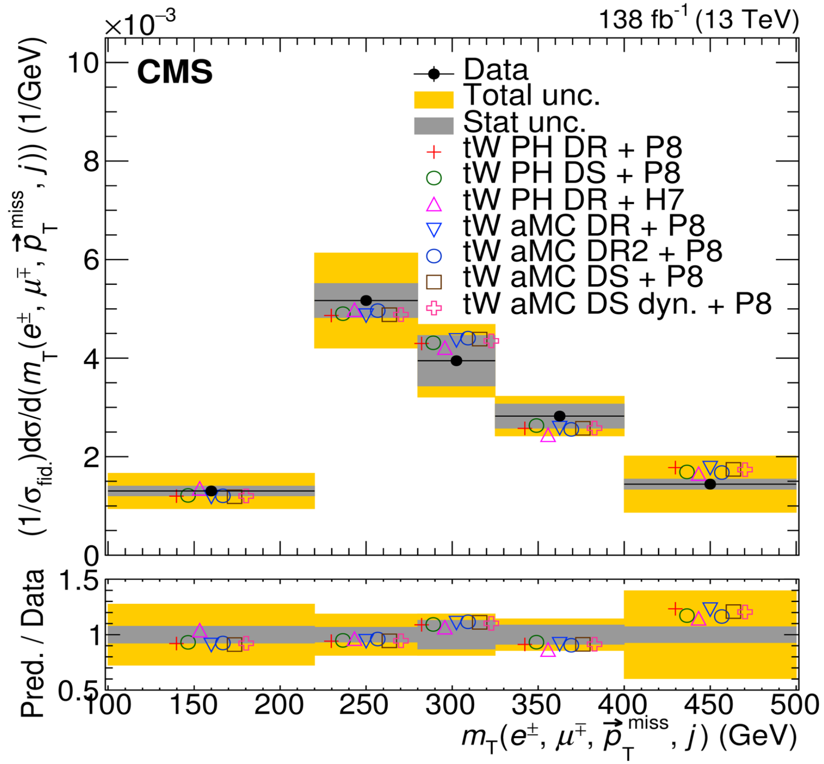
Probing couplings to:
➔Top quarks,
➔W bosons,
➔Gluons.



- We search for ALPs produced through the tW + a process at the LHC, using a reinterpretation of the CMS differential cross-section measurements for the tW production mode in pp collisions (JHEP07(2023)046: Run 2, 13 TeV).

- The analysis focuses on the opposite-sign, different-flavor dilepton final state: $e^{\pm}\mu^{\mp}$ which provides a clean experimental signature with reduced background contamination.

➢ The ALP modifies the kinematic distributions of the tW system through its couplings to the top quark, W boson, and gluons.
➢ Deviations in the CMS-measured differential tW cross section are used to set model-independent bounds on these couplings.
➢ This approach allows us to probe regions of parameter space not accessible through prompt ALP decay searches.



JHEP07(2023)046

ALP Production in the tW + a Channel

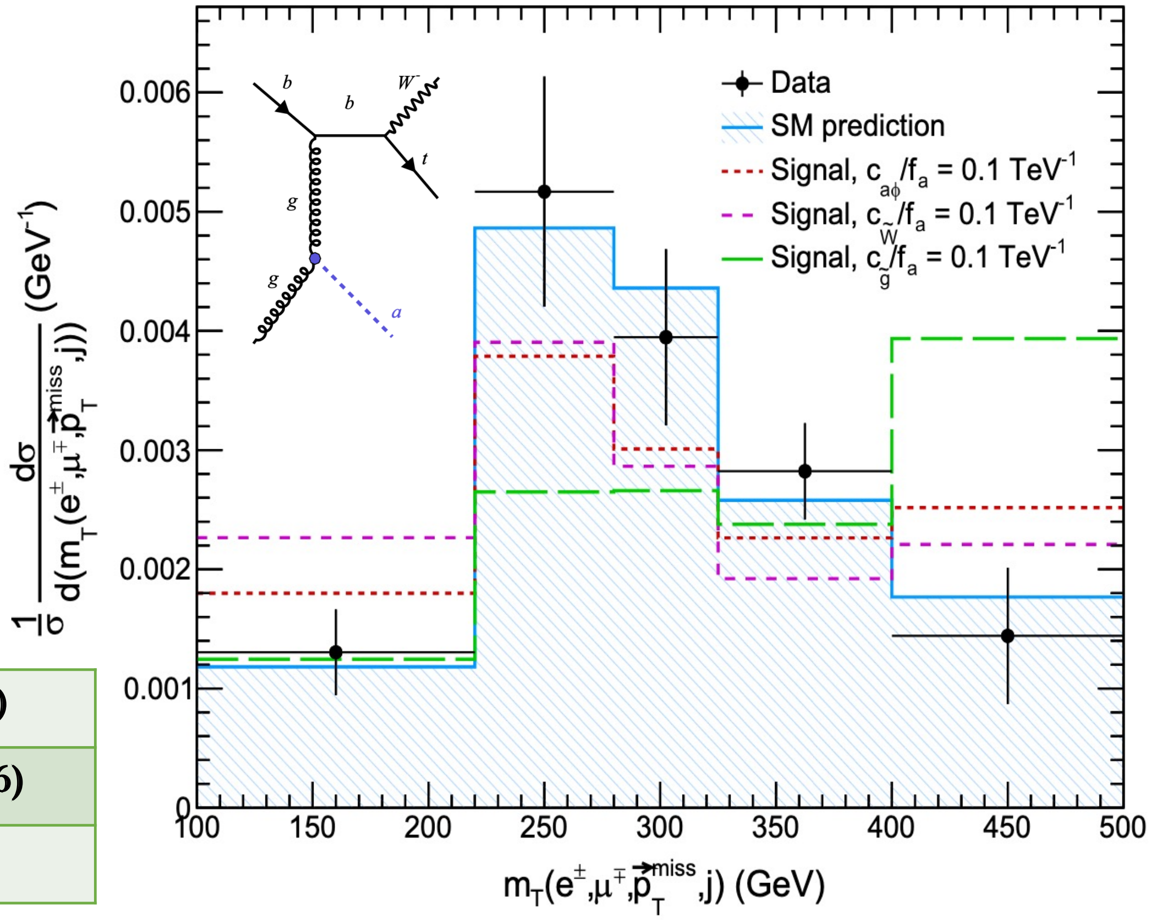
The ALP modifies the m_T distribution of the tW system through its couplings to the top quark, W boson, and gluons.

- **Additional MET from the invisible ALP.**
- **A boosted tW system recoiling against the ALP → c_G.**
- **A harder high-m_T tail from energetic ALP radiation.**

$$m_T = \sqrt{\left(|\vec{p}_{T,e}|+|\vec{p}_{T,\mu}|+|\vec{p}_{T,j}|+|\vec{p}_{T,miss}|\right)^2 - |\vec{p}_{T,e}+\vec{p}_{T,\mu}+\vec{p}_{T,j}+\vec{p}_{T,miss}|^2}$$

A hard ALP must be balanced by an oppositely directed tW system, and this recoil boosts the visible objects and enhances the m_T.

The ALP is invisible and carries transverse momentum, contributing directly to $\vec{p}_{T,miss} \approx \vec{p}_{T,a} + \vec{p}_{T,v1} + \vec{p}_{T,v2}$



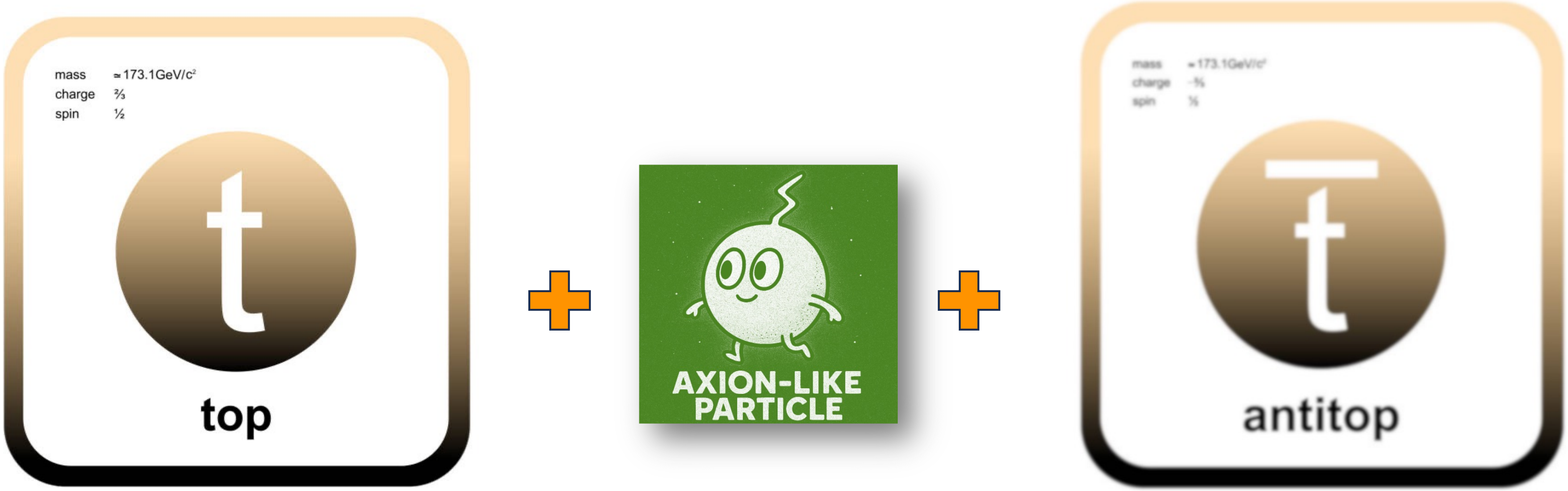
Performing fit to the distribution, limits at 95% CL for m_a = 1 MeV are:

IL	c_t (GeV^{-1})	c_G (GeV^{-1})	c_W (GeV^{-1})
Run II – 139 fb^{-1}	0.016 (0.500)	0.003 (0.097)	0.008 (0.246)
HL-LHC – 3 ab^{-1}	0.011	0.002	0.005

Will be improved with more data

Physical Review D 110, 055026 (2024)

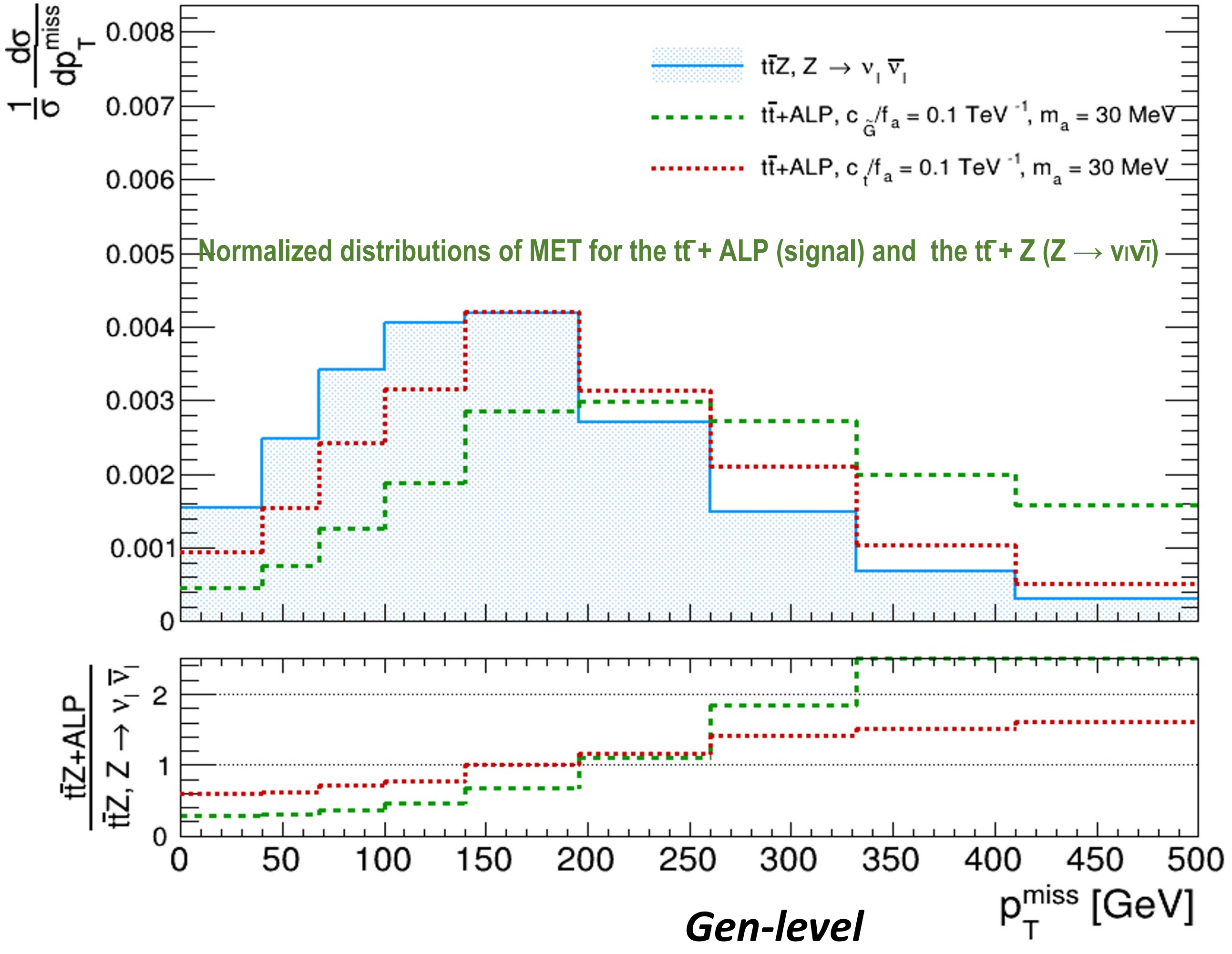
Ongoing Interpretation: $t\bar{t}$ + Z (→ Invisible) to Constrain $t\bar{t}$ + a



Ongoing Interpretation: $t\bar{t}$ + Z (→ Invisible) to Constrain $t\bar{t}$ + a

Since an invisible ALP produces the same signature as Z → νν, any additional contribution from $t\bar{t}$ + a can be bounded by this measurement.

- **The irreducible background contributing to the signal ($t\bar{t}$ + ALP) is $t\bar{t}$ + Z (Z → $\nu_l\bar{\nu}_l$).**
- **The p_T^{miss} distribution reveals that the signal ($t\bar{t}$+ALP) and the background ($t\bar{t}$ + Z (Z → $\nu_l\bar{\nu}_l$)) exhibit different behaviors at high missing energy values, with the signal displaying a longer tail compared to the backgrounds.**
- **Defining an ALP signal region at higher values of MET significantly improves the distinction between the signal and the irreducible background.**



Ongoing Interpretation: $t\bar{t}$ + Z (→ Invisible) to Constrain $t\bar{t}$ + a

- Use the fiducial cross-section measurement of $t\bar{t}$ + Z (→ νν) in events with large missing transverse momentum, to set model-independent bounds on $t\bar{t}$ + a (a → → → MET) .

- We apply a standard fiducial phase-space selection can be used by LHC experiments in the $t\bar{t}$ + Z (→ Invisible) measurement.

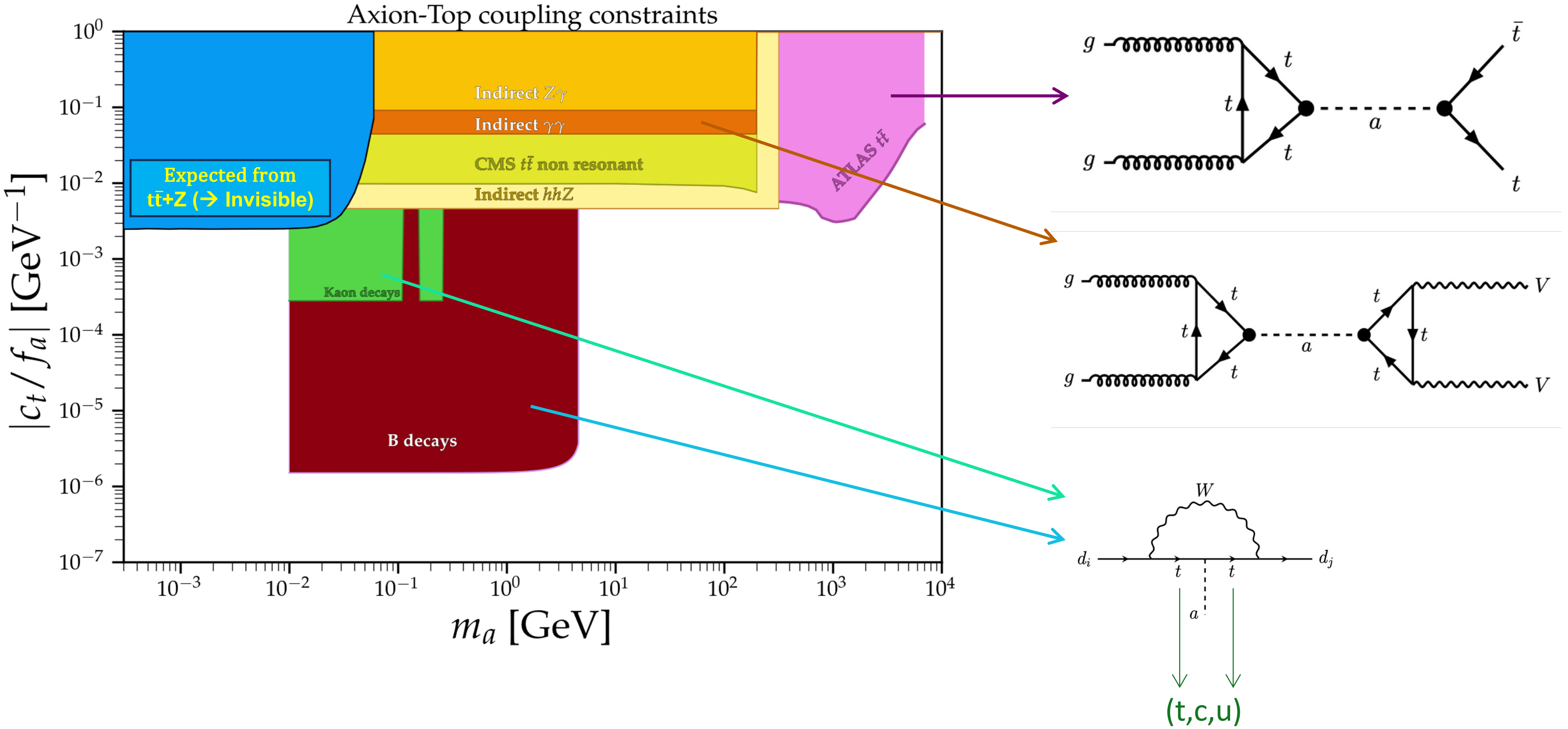
- We simulate the predicted yield of $t\bar{t}$ + a events in this region.

- To have a first rough estimation, we assume a 100% uncertainty on the fiducial $t\bar{t}$ + Z(νν) cross section → conservative treatment of systematic and theoretical and statistical uncertainties.

Fiducial Region

selection criteria	dileptonic channel
Object cuts:	
p_T(leading lepton) [GeV]	> 30
p_T(subleading lepton) [GeV]	> 20
$\|\eta\|$(lepton)	$< 2.4^*$
p_T(jet) [GeV]	> 30
$\|\eta\|$(jet)	< 2.4
ΔR(lepton, jet)	> 0.4
Event requirements:	
Number of leptons	$= 2$
$Q(\ell_1) \times Q(\ell_2)$	-1 (opposite charge)
$m_{\ell_1\ell_2}$ [GeV]	> 20
$m_{e^-e^+}$ or $m_{\mu^-\mu^+}$ [GeV]	< 76 or > 106 (exclude Z window)
Number of jets	≥ 2
Number of b-jets	≥ 1
p_T^{miss} [GeV]	> 150

BSM Interpretation: $t\bar{t}$ + Z (→ Invisible) to Constrain $t\bar{t}$ + a



Constraints at 95% CL on ALP-top coupling versus the ALP mass are shown. The blue region correspond to the results obtained from the tt+ALP search conducted in this study. Other regions represent results taken from [JHEP 09 (2023) 063],[2404.08062],[Phys. Rev. Lett. 118, 111802].

Summary and Conclusions

1. LHC searches for invisible ALPs are powerful and complementary to cosmology and beam-dump experiments. Collider-stable ALPs are an especially under-explored region where LHC analyses are uniquely competitive.

2. Production in association with top quarks ($t\bar{t}$ + a and tW + a) provides a clean and direct probe of:

ALP–top couplings ; ALP–gluon couplings ; ALP–W boson couplings

3. Our interpretations of existing CMS data deliver new bounds:

- $t\bar{t}$ + MET recast constrains c_G/f_a down to ~10^{-3}–10^{-4} GeV^{-1} for light ALPs
- tW differential cross section probes c_t, c_G, c_W simultaneously
- $t\bar{t}$ + Z (→νν) can provide bounds in a high-MET fiducial region → constrains c_t/f_a down to ~10^{-3} for m_a <~ 100 MeV

4. FCC-hh dramatically improves reach, probing c_G/f_a down to 10^{-6} GeV^{-1}, opening regions far beyond HL-LHC and bridging to beam-dump sensitivities. And c_t/f_a down to 10^{-4} GeV^{-1}

5. Together, these results build a coherent picture:
LHC + HL-LHC + FCC-hh offer a continuous and expanding exploration of invisible ALPs across orders of magnitude in couplings.

Thanks for your attention

Backup

ALP Effective Lagrangian

- Effective Lagrangian:

[Eur.Phys.J.C 77 (2017) 8, 572]

$$\mathcal{L}_{eff} = \mathcal{L}^{LO} + \delta\mathcal{L}_a^{total}$$

$$\mathcal{L}^{LO} = \mathcal{L}_{SM} + \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2} m_a^2 a^2$$

$$\mathcal{L}_{SM} = D_\mu \phi^\dagger D^\mu \phi + \sum_\psi i\,\bar{\psi}\,\gamma^\mu D_\mu\,\psi - (\bar{Q}_L Y_D \phi d_R + \bar{Q}_L Y_U \tilde{\phi} u_R + \bar{L}_L Y_E \phi e_R + h.c.)$$

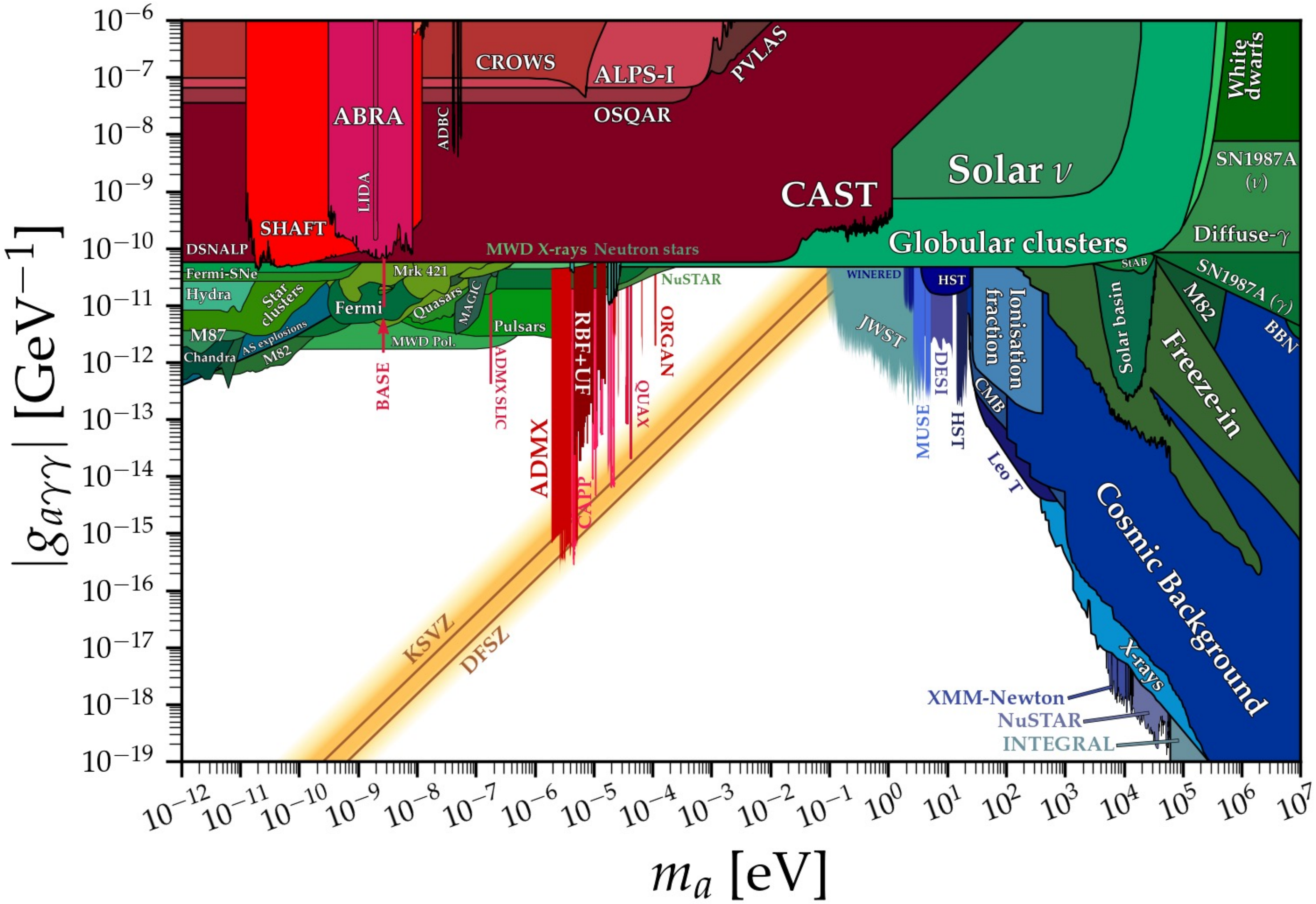
$$\delta\mathcal{L}_a^{total} = c_{\tilde{W}} A_{\tilde{W}} + c_{\tilde{B}} A_{\tilde{B}} + c_{\tilde{G}} A_{\tilde{G}} + c_{a\phi} O_{a\phi}^{\psi}$$

$$A_{\tilde{W}} = -W_{\mu\nu}^a \tilde{W}^{a\mu\nu} \frac{a}{f_a}$$

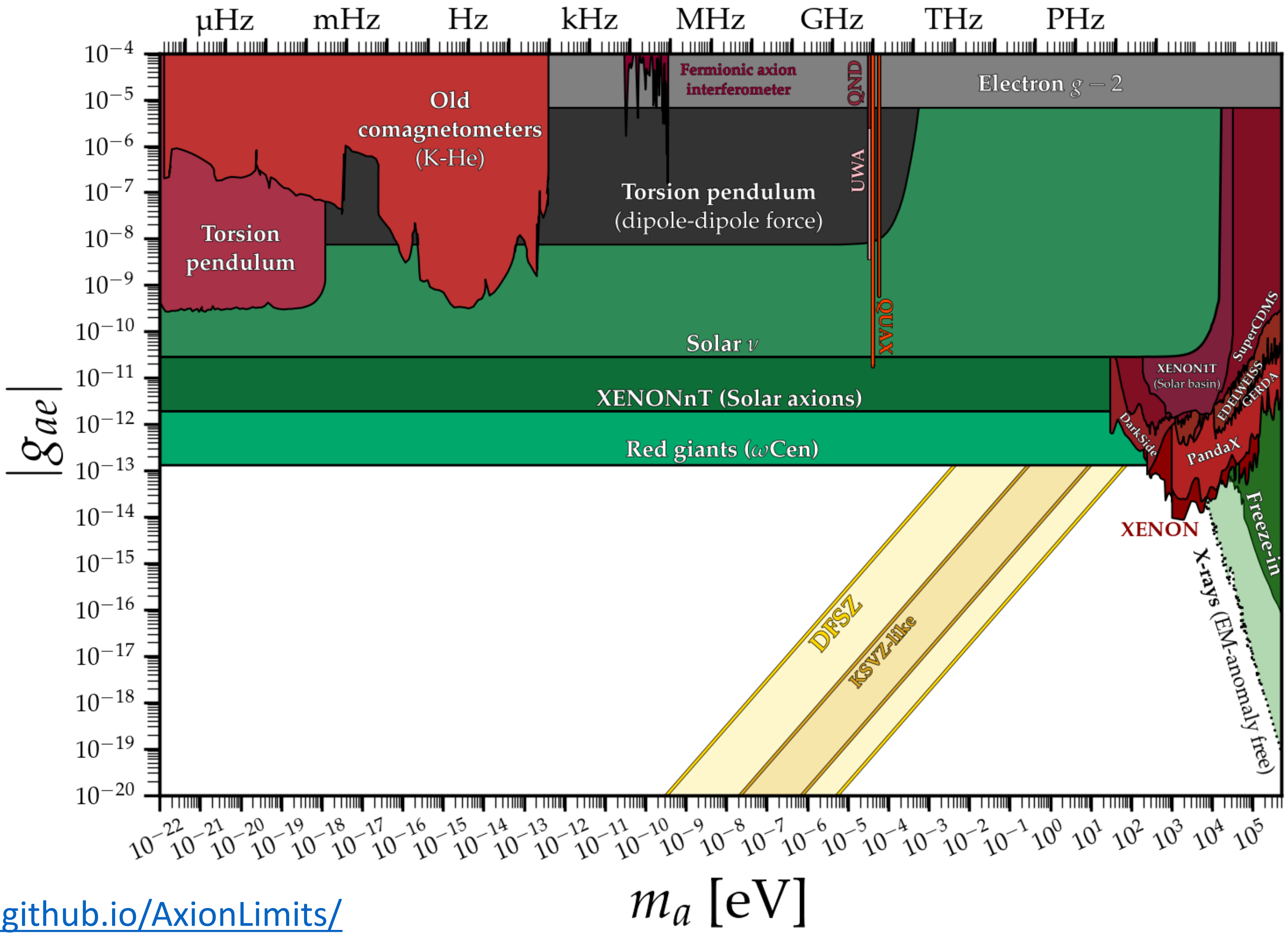
$$A_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu} \frac{a}{f_a}$$

$$A_{\tilde{G}} = -G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \frac{a}{f_a}$$

$$O_{a\phi}^{\psi} = i\,(\bar{Q}_L Y_U \tilde{\phi} u_R - \bar{Q}_L Y_D \phi d_R - \bar{L}_L Y_E \phi e_R)\frac{a}{f_a} + h.c.$$

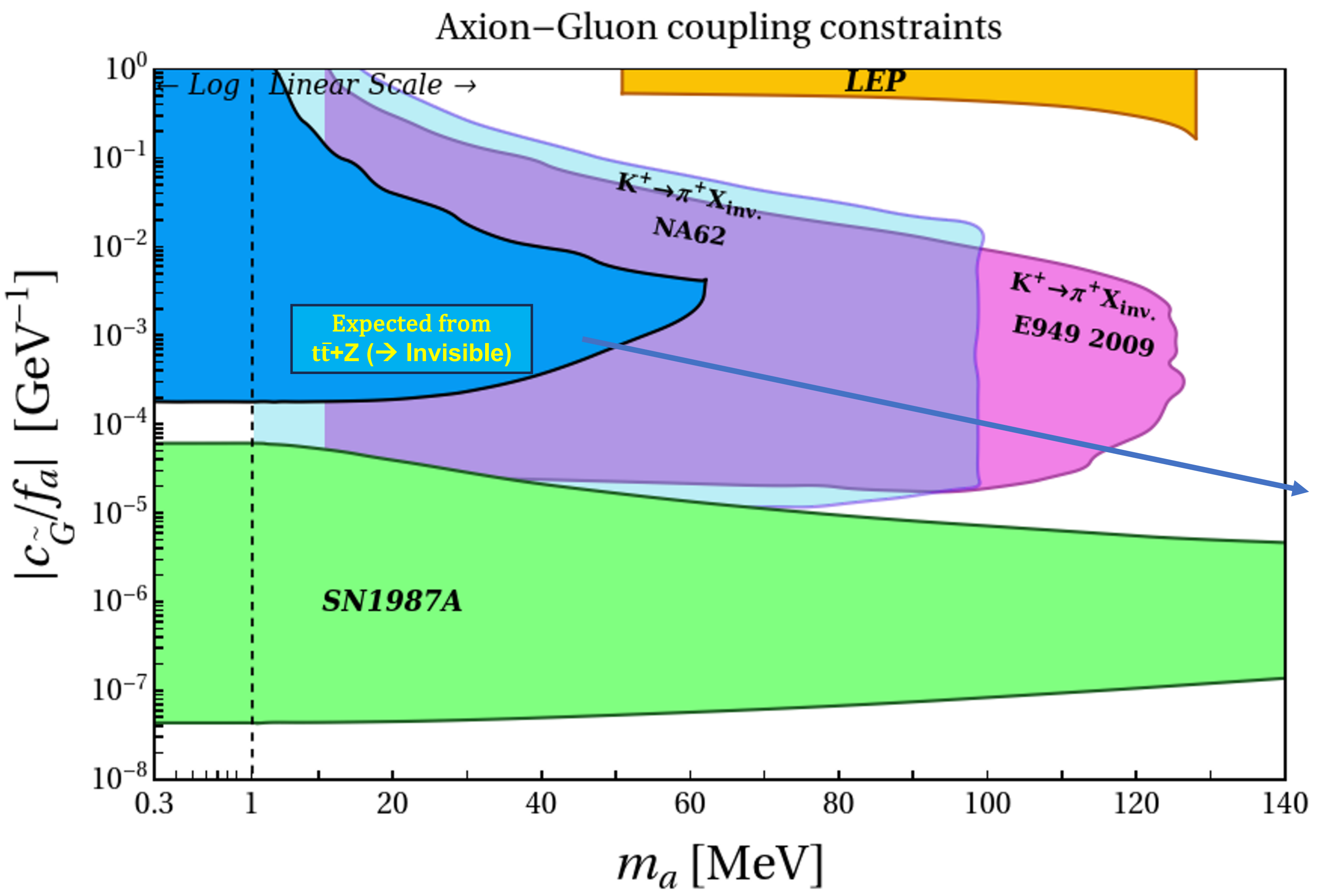


https://cajohare.github.io/AxionLimits/



https://cajohare.github.io/AxionLimits/

BSM Interpretation: $t\bar{t}$ + Z (→ Invisible) to Constrain $t\bar{t}$ + a



Assume a 100% uncertainty on the fiducial $t\bar{t}$ + Z(vv) cross section

- Exclusion 95% CL limits in the ALP-gluon coupling versus the ALP mass are shown. The blue region denotes the limits derived from the tt+ALP search performed in this study. Other regions are adopted from [Rept. Prog. Phys. 86 (2023), no. 1, 016201],[JHEP 07 (2020), 050].

Simulation Setup

Event Generation and Simulation:

- The ALP effective Lagrangian has been implemented into FeynRules.
- The resulting Universal FeynRules Output (UFO) model was then imported into MadGraph5_aMC@NLO,
- The signal events are generated for scenarios where, in each case, only one of the ALP couplings is non-zero.
- Events are then passed through PYTHIA 8 for showering, hadronization and decay of unstable particles.
- For some studies --> Delphes 3 (upon need).

To determine the exclusion limits on (c_G / f_a) and (c_t / f_a) as a function of ALP mass, different samples are generated for m_a including: m_a = 0.3, 0.4, 0.5, 0.8, 1, 2, 3, 4, 5, 7, 9, 12, 15, 18, 22, 27, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 120, 140, 150 MeV.