A Phenomenological and Experimental Perspective on

Probing Light Axion-Like Particles at the LHC and Future Colliders

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Jury: F. Ledroit-Guillon (Pres.) | **Rapporteurs**: J. Andrea, F. Mahmoudi, J. Ocariz | **Examinateurs**: E. Chabert, J. Collot, M.-H. Genest, S. Kraml

Outline of the Presentation

I — Part I — Scientific Trajectory & Motivation for ALPs

- My general scientific trajectory and research vision
- Scientific strategy: invisible sectors at colliders
- Motivations for ALPs

II — Part II — Collider Program for Invisible ALPs

- dijet + ETmiss, γ+j+ETmiss — gluon sector
- $t\bar{t}$+a: heavy-quark recoil (LHC & FCC-hh)
- Gauge boson couplings: VVa, V+jets, 2D limits
- Unfolded top measurements as ALP probes

III — Part III — Experimental Realization at CMS

- CMS $t\bar{t}Z(Z\to\nu\bar{\nu})$ analysis — 138 fb^{-1}, Run 2 (+3)
- Reinterpretation as $t\bar{t}$+a: methodology & limits
- BDTs, systematics, …

Ongoing

IV — Part IV — Future Directions & Research Program

- Muon collider: LFV ALPs with beam polarization
- ILC: light dark sector via Higgs portal
- Future collider ecosystem

Scientific Trajectory: Key Milestones & Evolution

2000–02 — **MSc – Noncommutative QED/ Sharif Univ.**
- Noncommutative QED β-function & conformal anomaly

2002–07 — **PhD – CERN/CMS + Sharif Univ.**
- t-channel single top at 14 TeV
- HF Calorimeter test & calibration

2007–12 — **Postdoc IPM/CMS**
- Top quark and Higgs anomalous couplings (FCNC, dipoles)
- Search for large extra dimensions (CMS)

2012–16 — **Researcher IPM/CMS**
- Top quark EFT (SMEFT), W-helicity dilepton - CMS
- Top FCNC with photon — CMS 8 TeV
- Phenomenology of SMEFT Studies

2016–25 — **Team Leader of IPM @ CMS**
- IPM CMS group + RPC upgrade Link & Control Board
- First Observation of SM t + γ published in PRL
- Top FCNC with photon — CMS 13 TeV
- ALP studies
- Lepton collider studies

2023– — **CERN Project Associate (PJAS)**
- CMS Outer Tracker Upgrade
- ALP program completion, HL-LHC strategies
- HDR submitted & defense (2025-2026)

Supervision Record

PhD Students 5 + (4 → co-supervisor)

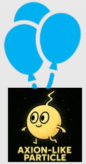
Reza Goldouzian *FCNC t-q-γ (CMS)*	2012–16	Now at Notre Dame U.
Sara Khatibi *BSM via top quark*	2012–17	Now at Tehran U.
S.M. Etesami *Extra dimensions @ CMS*	2010–14	Now at IPM
Javad Ebadi *ALP–top searches, SMEFT*	2016–20	Now at Calgary, Data Science
Yasaman Hosseini *tt̄Z → tt̄+a and RPC Eff (CMS)*	2020–24	Now at IPM

Postdoctoral Researchers 4 + (4 postdoc collaborators)

H. Khanpour	2014–20	Now at AGH Cracow
F. Elahi	2018–20	Now at Mainz U.
G. Haghighat	2019–22	Now at IHEP-China
S. Taheri Monfared	2012–15	Now at DESY

Part I

Motivations



Why Axion-Like Particles?

Well-motivated candidates for new physics.

- Pseudo-Nambu–Goldstone bosons arising from spontaneously broken global symmetries.
- Predicted in many extensions of the SM:
  - **- Flavor symmetry models.**
  - **- Peccei–Quinn (PQ) symmetry,**
  - **- Composite Higgs models.**

Unique theoretical properties

- CP-odd pseudoscalar particles protected by an approximate **shift symmetry**, a → a + cte.
- Interact with Standard Model particles mainly through **dimension-5 effective operators**, leading to derivative, momentum-dependent couplings.

Motivation & Scientific Positioning

Why colliders?

-Production rates increase with momentum transfer, making high-energy colliders particularly sensitive to ALPs.

-Depending on their mass and couplings, ALPs may appear as:

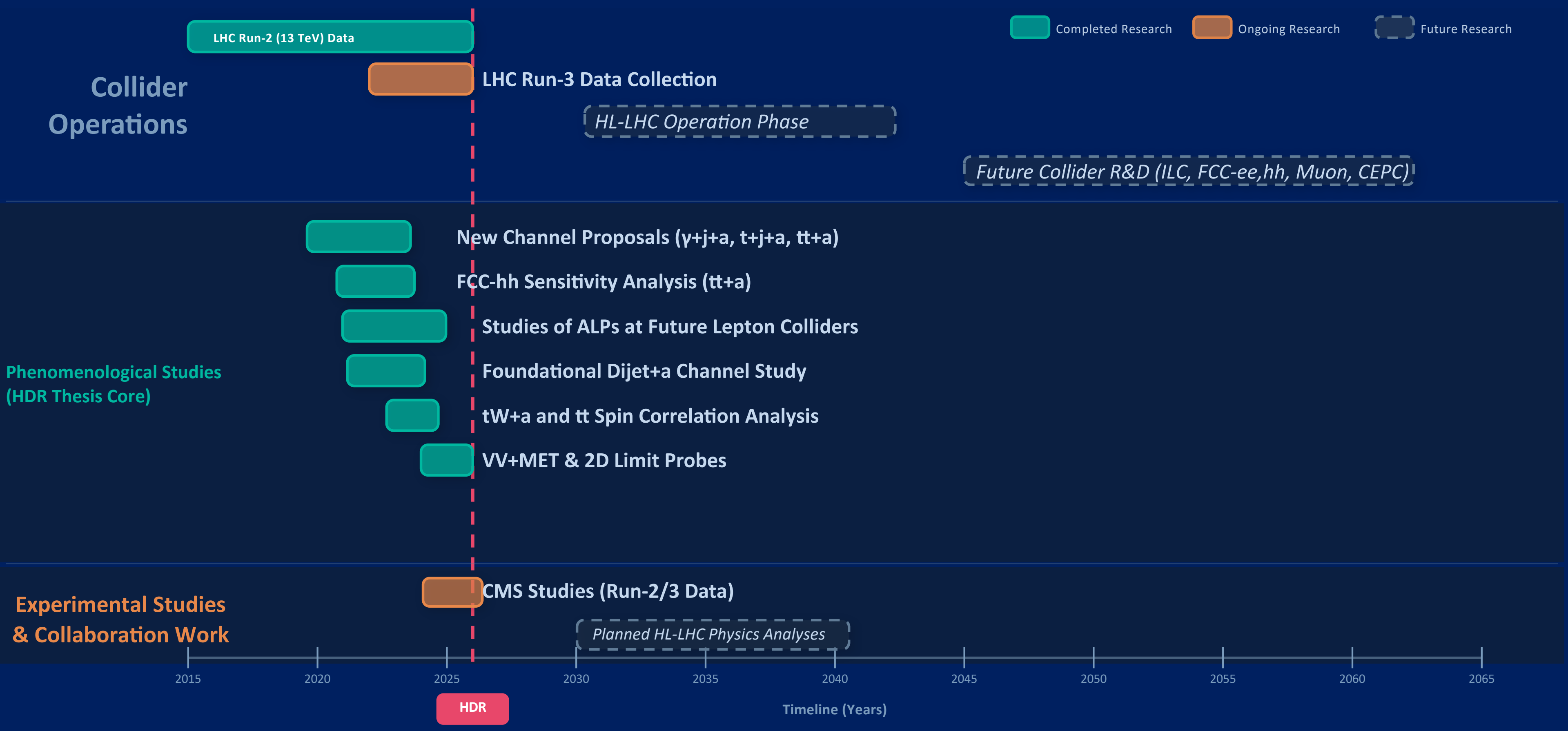
- resonances,
- long-lived particles,
- invisible particles producing missing transverse momentum.

Scientific focus of this HDR

Strategic choice: Develop a coherent collider program targeting **collider-stable (invisible) ALPs**, combining phenomenology, CMS analyses, and future collider studies within a unified EFT framework.

- Separable from SM neutrino-MET through recoil kinematics — **no resonance bump needed**
- Exploitable at every collider: hadron, e^-e^+, muon
  → the multi-environment program

Research Trajectory: Searches for Light ALP Studies at Colliders



Scientific Vision: A Unified Collider Program for Light Invisible ALPs

Guiding Principle: Invisible new degrees of freedom are revealed through the kinematic structure of the visible systems recoiling against them.

1 Channel Diversity

Never rely on a single channel Complement hadronic, top, gauge boson sectors

Each channel independently constrains different combinations of EFT operators

Multi-channel combination → removes degeneracies

2 Theory-to-Experiment Pipeline

Develop phenomenological analysis chain validated against CMS reconstruction

Directly feed designs into CMS collaboration analyses — not just external proposals

Ensure all projections are experimentally realistic

3 Collider Ecosystem Vision

LHC → HL-LHC → FCC-hh (energy frontier) Muon collider (LFV, new couplings) ILC (Higgs portal, invisible Higgs)

Consistent EFT framework across all environments

Map the full ALP parameter space systematically

Originality: Developed the first coherent collider program for invisible ALPs, combining complementary search channels within a common EFT framework and bridging phenomenological studies with CMS experimental implementation.

Research Impact & Output

Publication Record (HDR Program 2019–2025)

These seven papers progressively built the collider program that I will describe.

[1]	Ch.3	**New probes for ALPs at hadron colliders and ALP probes at future hadron colliders via top-quark associated production**	*PRD 100:015016 (2019)* *Universe 8:301 (2022)*
[2]	Ch.3	**New collider searches for ALPs coupling to gluons — dijet+MET at 13/27/100 TeV — first systematic BDT-based ALP invisible study**	*PRD 102:115010 (2020)*
[3]	Ch.4	**Measurement of Top Quark Pair Production in Association with Invisible Z Boson Decay and Axion-Like Particle Interpretation at $\sqrt{s}$ = 13 TeV**	→ CMS Ongoing analysis CMS PAPER TOP-24-005
[4]	Ch.5	**ALP constraints from unfolded tW and $t\bar{t}$ spin-correlation measurements**	*PRD 110:055026 (2024)*
[5]	Ch.6	**Concurrent ALP–gauge boson interactions: VVa + V+jets 2D limits**	*Nucl.Phys.B 1018 (2025)*
[6]	Ch.7	**LFV ALPs at future muon collider with beam polarization**	*Nucl.Phys.B 980 (2022)*
[7]	Ch.8	**Light dark sector at future lepton colliders via invisible Higgs decays**	*PRD 107:035033 (2023)*

7 | Peer-reviewed papers

2 | PhD students supervised

2 | Postdocs mentored

3 | Collider environments

2D | Coupling limits (novel)

Theoretical Framework: ALP Effective Field Theory

ALP EFT Lagrangian (dimension-5 operators):

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

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

Key Parameters

m_a	ALP mass	Free parameter (independent of f_a)
c_{GG}/f_a	ALP–gluon coupling	Dominant at hadron colliders
c_{WW}/f_a	ALP–EW boson coupling	Probed via VVa, V+jets
c_t/f_a	ALP–top coupling	Via Higgs-current operator (caΦ)
$c_{\tau e}$, $c_{\tau\mu}/f_a$	LFV ALP couplings	τ→ℓa at muon collider

Three Collider Regimes

Prompt Decay

ALP decays inside detector → visible products

Displaced Vertex

Macroscopic decay length → exotic signature

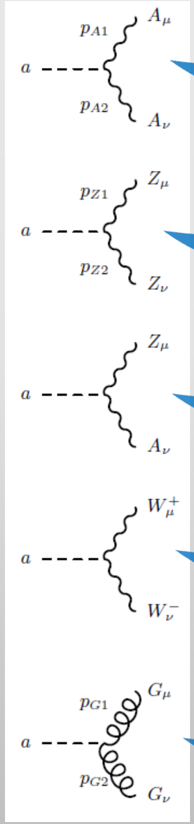
Invisible (This Work) ★

ALP escapes detector → missing transverse momentum

Axion-Like Particles couplings to SM

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

Vertices:



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

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

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

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

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

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

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

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

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

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

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 → a + 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)

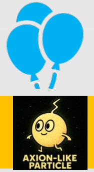
$$\mathcal{L} = -i\, c_t \frac{m_t a}{2 f_a} (\bar{t}\gamma^5 t)$$

- 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.

Part II

Hadron Collider Program for Invisible ALPs

One coherent story: gluon sector → top sector → gauge boson sector → unfolded precision



c_{GG}/f_a

Gluon sector

dijet+MET, γ+j+MET, $t\bar{t}$+MET

PRD 100:015016 (2019)
PRD 102:115010 (2020)

c_{WW}/f_a , c_{GG}/f_a

EW sector

ZZa, WWa, V+jets unfolded

Nucl.Phys.B 1018 (2025)

c_t/f_a

Top sector

$t\bar{t}$+a, tW+a, $t\bar{t}$ spin corr.

PRD 110:055026 (2024)

The Invisible-ALP Collider Program: One Coherent Physics Story

I designed a progressive, multi-channel campaign — each channel addressing a different ALP coupling and kinematic regime:

1 Hadronic Recoil

dijet + a (P_{Tmiss})
γ+j + a (P_{Tmiss})

Coupling probed:

c_{GG}/fa
c_{WW}/fa

PRD 100:015016 (2019)
PRD 102:115010 (2020)

2 Heavy Quark Recoil

tt̄ + a (P_{Tmiss})
LHC + FCC-hh

Coupling probed:

c_{GG}, ct/fa

Universe 8:301 (2022) @FCC-hh
PRD 100:015016 (2019)

3 Gauge Boson Sector

ZZa, WWa
V+jets+a unfolded

Coupling probed:

2D: c_{WW}, c_{GG}/fa

Nucl.Phys.B 1018 (2025)

4 Precision Probes

tW+a, tt̄ spin corr.
unfolded measurements

Coupling probed:

ct, c_{GG} 2D

PRD 110:055026 (2024)

Key innovation: designed as mutually reinforcing — each channel fills blind spots of the others, enabling true 2D coupling constraints

ALP recoils against jets/photons/V/top, producing P_{Tmiss} harder than SM neutrinos

ALP Behaviours: Parameter Space and Strategy

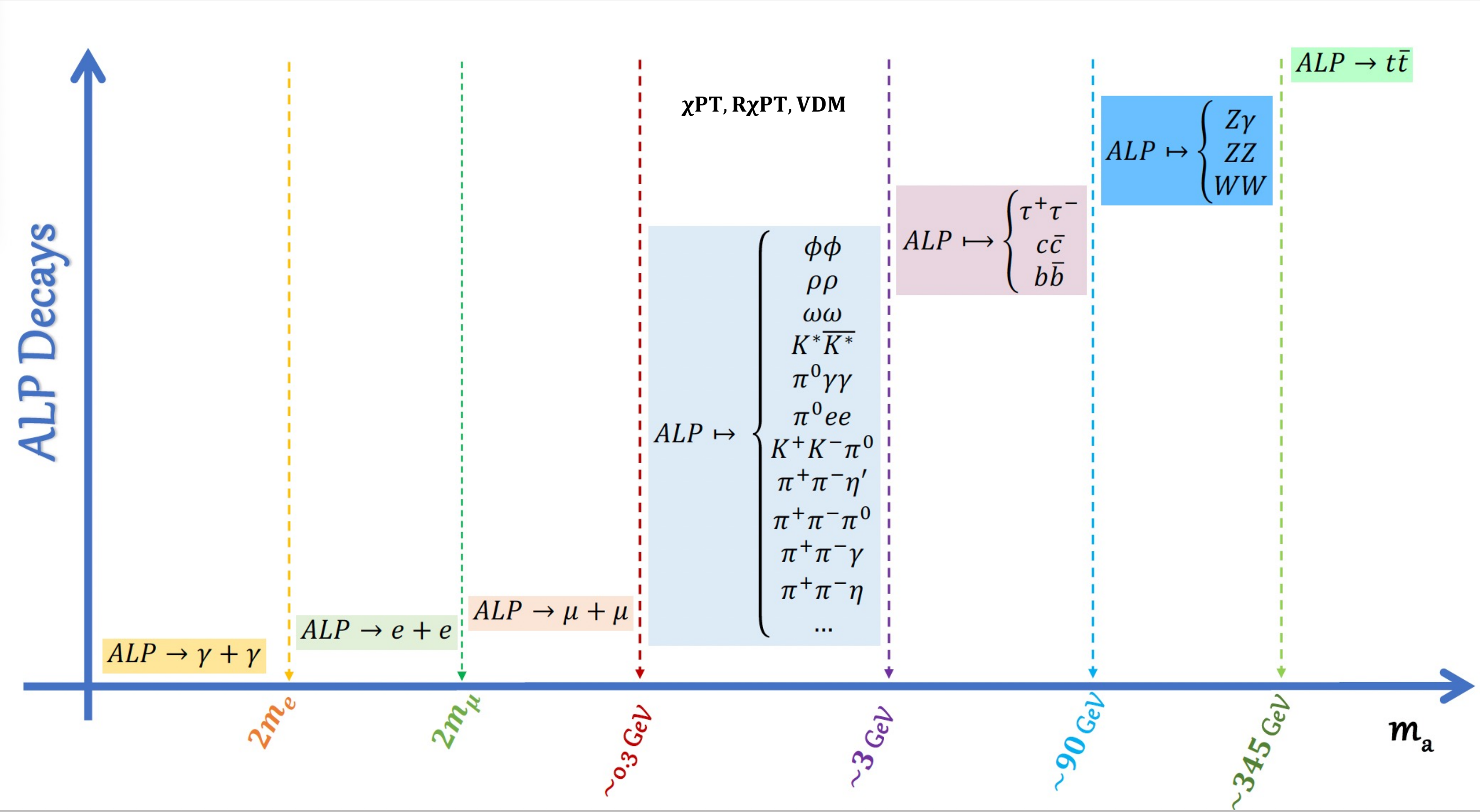
The phenomenology of ALPs at the LHC depends crucially on their mass and decay width, or equivalently, their lifetime or proper decay length. Depending on these parameters, ALPs can give rise to very different experimental signatures.

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

Behaviour	Proper Decay Length $c\tau_a$	Dominant Decay Modes / Signature
Collider-stable (invisible)	$> L_{det.} \sim O(10)$ m	None (ALP escapes); MET + jets/leptons/photons
Long-lived (displaced)	few mm to L_{det}	$\gamma\gamma$, 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	Prompt resonances depending on the mass: $\gamma\gamma$, e^+e^-, hadronic, $\bar{c}c$, $b\bar{b}$, $\tau^+\tau^-$, WW, ZZ, Zγ, $t\bar{t}$. Appear as resonances in various visible final states
Virtual (off-shell)	$\ll 10^{-15}$ m	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 decay modes



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:

$$P_{decay} = 1 - e^{-L^T_{Det}/L_a}$$

Where L^T_{Det} 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:

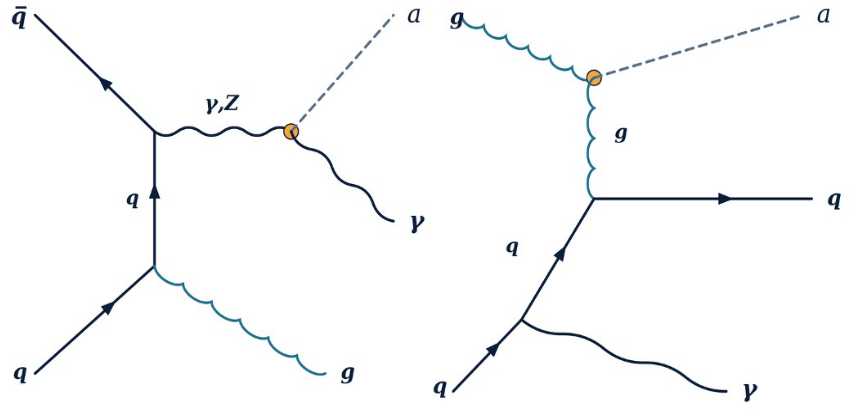
m_a = 1 MeV and $\frac{c_{\gamma\gamma}}{f_a} < 10^{-12}\ \mathrm{GeV}^{-1}$ →→→ $L_a \gtrsim (2.3 \times |p_a|) \times 10^{21}$ m.

From Supernova SN1987a

CHANNEL 1 — jet + γ + a

Production mechanism and cross sections

Sensitive to ALL ALP couplings at once: c_{WW}, c_{BB}, c_{GG}, $c_{a\Phi}$



Leading-order √s = 14 TeV cross sections (single coupling at a time, m_a = 1 MeV)

Coupling	σ [pb] × $(f_a/c)^2$ [TeV²]
$\sigma(c_{GG})$	30.0
$\sigma(c_{WW})$	13.9
$\sigma(c_{BB})$	14.4
$\sigma(c_{a\Phi})$	0.36 (negligible → not considered)

Key features

- Initial states with a gluon (gq, gq̄) dominate over qq̄ annihilation — large gluon PDF at low x ⇒ strongest sensitivity to c_{GG}
- Cross sections essentially independent of m_a for $m_a \lesssim$ few GeV (m_a negligible vs. process energy scale)
- Beam-dump bound fixes $|c_{BB} \cos^2\theta w/f_a + c_{WW} \sin^2\theta w/f_a| \leq 2.5\times10^{-3}$ for $m_a \leq 1$ MeV → c_{BB} folded into the c_{WW} limit

CHANNEL 1 — jet + γ + a

Event selection and backgrounds

Selection requirements, cut and count

- Exactly 1 isolated photon: pT ≥ 40 GeV, |η| ≤ 3.0, I_rel < 0.15
- ≥ 1 jet: p_T ≥ 30 GeV, |η| ≤ 4.0; < 3 jets, ≤ 1 b-jet (suppress $\bar{t}t\gamma$)
- ΔR(i,j) ≥ 0.4 between all objects
- Δϕ(j,γ) ≤ 2.7 (signal is not back-to-back, unlike γ+j)
- $H_T \geq 200$ GeV (scalar p_T sum of final-state objects)
- $E_T$miss ≥ 90 GeV (optimized for c_{GG}) or ≥ 50 GeV (for c_{WW})
- Validity of EFT: require E_T^miss < f_a event-by-event

Backgrounds

- $Z(\to\nu\bar{\nu})+\gamma+j$ — irreducible; estimated data-driven from $Z(\to\mu\mu)+\gamma+j$
- $W(\to\ell\nu)+\gamma+j$, $\bar{t}t\gamma$, $t\gamma j$ — lepton out of acceptance
- γ+j — fake E_T^miss from jet mis-measurement

Cut-flow efficiency

Cut	c_{GG} sig.	c_{WW} sig.	Zγ+j	γ+j
jet & photon	0.591	0.728	0.636	0.431
Δϕ(j,γ)≤2.7	0.503	0.402	0.464	0.087
E_t^{miss} ≥ 90 GeV	0.365	0.031	0.216	3.7×10^{-5}

CHANNEL 1 — jet + γ + a

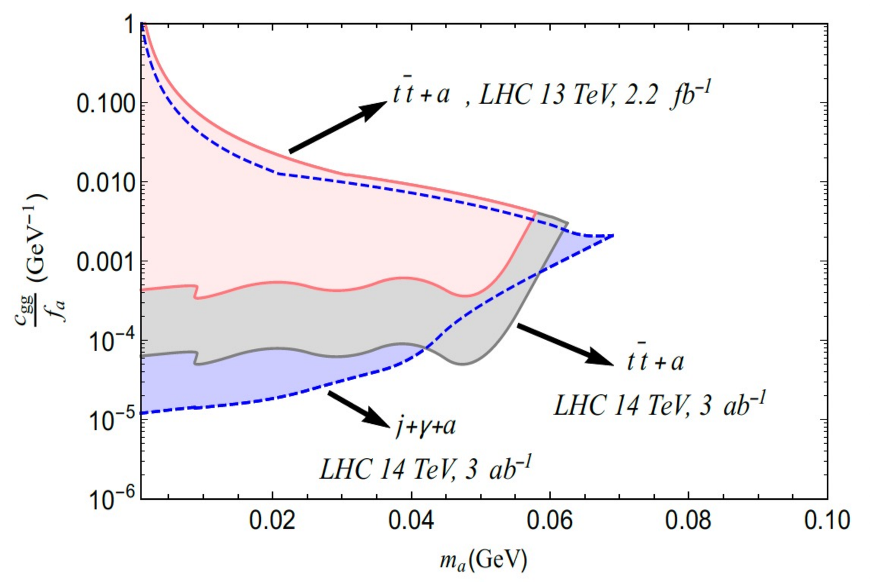
Sensitivity at 3000 fb^{-1} (HL-LHC)

$|c_{GG}/f_a| \leq$ 0.012 TeV^{-1}

for m_a = 1 MeV — comparable to 8 TeV monojet (0.025 TeV^{-1}) with 150× less data

$|c_{WW}/f_a| \leq$ 0.041 TeV^{-1}

for m_a = 1 MeV — best of all single-photon-coupling channels studied

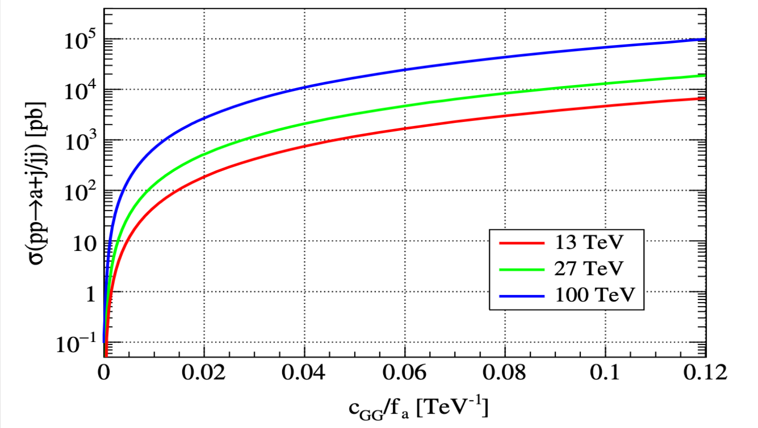


vs. other LHC channels for c_{WW} (95% CL, 3000 fb^{-1}, 13 TeV):

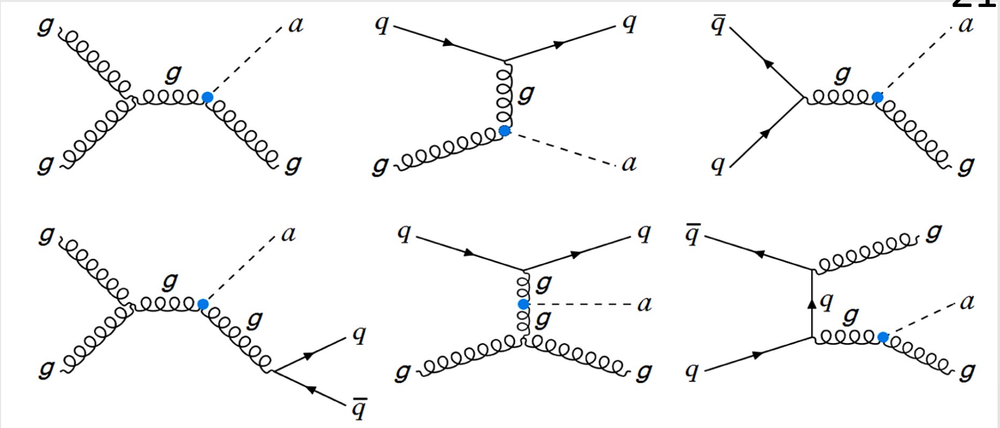
mono-photon ≤ 0.14 TeV^{-1} · mono-Z ≤ 0.05 TeV^{-1} · mono-W ≤ 0.16 TeV^{-1}

CHANNEL 2 — jet + (jet)+ a

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



- MadGraph5_aMC@NLO → hard process + cross sections
- MLM matching merges a+j and a+jj samples (xqcut=10, qcut=25 GeV) — same scheme used for multijet, W+jets, Z+jets merging.
- Pythia 8.2.43 → showering, hadronization, decays.
- Delphes 3.4.2 → upgraded CMS detector response.
- FastJet, anti-k_T, R = 0.4 → jet reconstruction.



Why c_{GG} dominates

- $\sigma(c_{a\Phi}/f_a) = 0.225 \times (c_{a\Phi}/f_a)^2$ pb, 6 orders of magnitude < c_{GG} rate
- ALP–fermion couplings are Yukawa-suppressed (up/down quarks)

Dominant SM backgrounds

- **Multijet production — dominant background, well suppressed by selection**
- VV (V=W,Z), hadronic + leptonic decays
- W+jets, Z+jets, γ+jets (all final states)
- t̄t and single top (s, t, tW channels, all final states)

Multivariate signal-background discrimination

Validity of the effective theory

Require $\sqrt{\hat{s}} < f_a$ event-by-event. E_T^{miss}, $< f_a$ as a conservative proxy, discarding events that violate $\sqrt{\hat{s}} > 2E_T^{miss}$.

HLT-level requirements

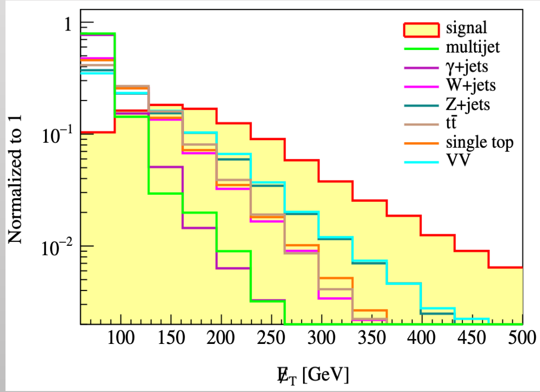
$E_T^{miss} > 60$ GeV and p_T(hardest jet) > 180 GeV, |η|<2.5

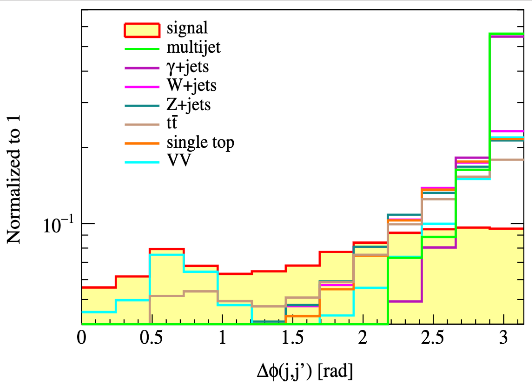
2 or 3 reconstructed jets, pT > 30 GeV, |η|<2.5; veto isolated photons/leptons with pT > 10 GeV, |η|<2.5 (Irel<0.12 γ/e, <0.25 μ)

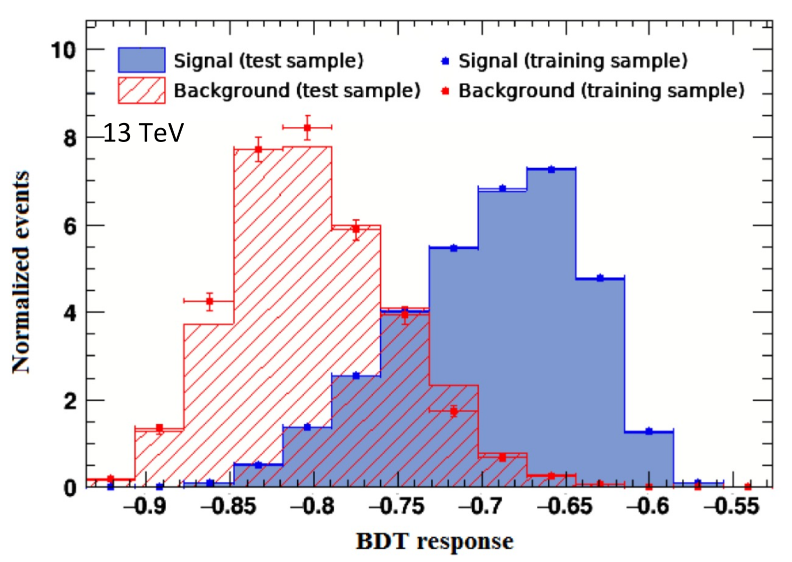
Discriminating variables (BDT input)

- Missing transverse energy E_T^{miss}
- Scalar p_T sum H_T
- $\Delta\phi(E_T^{miss}$, hardest jet) and $\Delta\phi(j,j')$
- p_T, η of the 1st and 2nd hardest jets

Most powerful: E_t^{miss} and $\Delta\phi(j,j')$

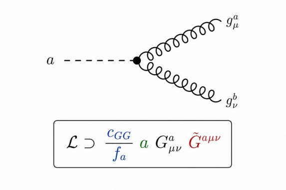




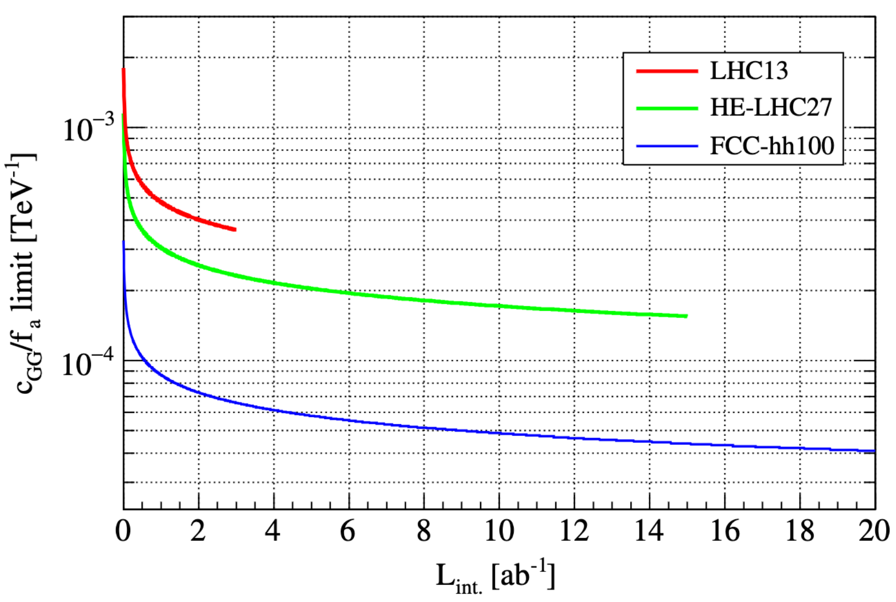


RESULTS CHANNEL 2 — dijet + a

Expected 95% C.L. limits on c_{GG}/f_a



vs. integrated luminosity (m_a = 1 MeV, with systematics)



LHC13

4.5×10^{-4} TeV^{-1}

ultimate limit @ 3 ab^{-1}

HE-LHC27

1.9×10^{-4} TeV^{-1}

ultimate limit @ 15 ab^{-1}

FCC-hh100

5.0×10^{-5} TeV^{-1}

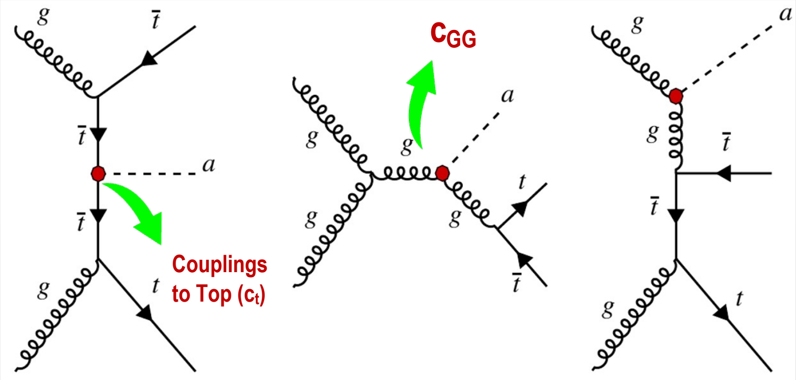
ultimate limit @ 20 ab^{-1}

CHANNEL 3 & 4: ALP Production Channels Associated with Top quark

Two production channels at the LHC:

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

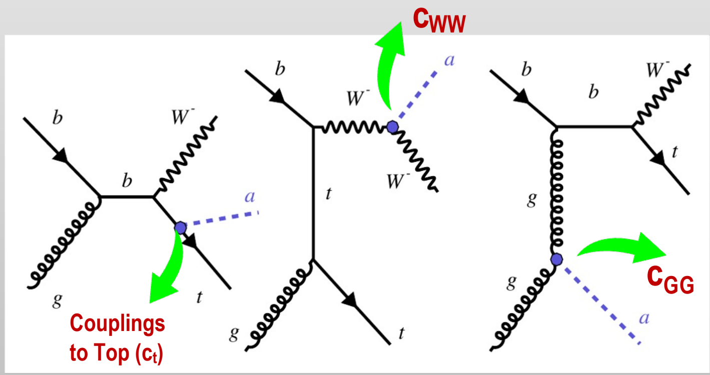
– $t\bar{t}$ + a ($t\bar{t}$ + MET)



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 Production in the tW + a (tW + MET)

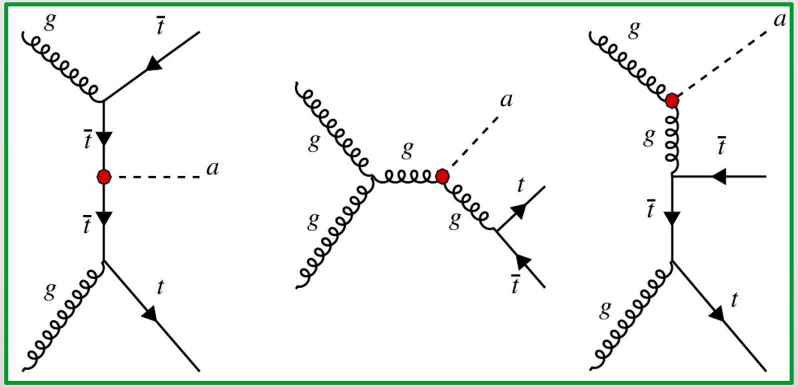


Physical Review D 110, 055026 (2024)

CHANNEL 3: $t\bar{t}$ + 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→νν)
- 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:

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

At high-energy:
-Low-pT (MET) region: the cross section grows like $1/p_{T,a}$, 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).

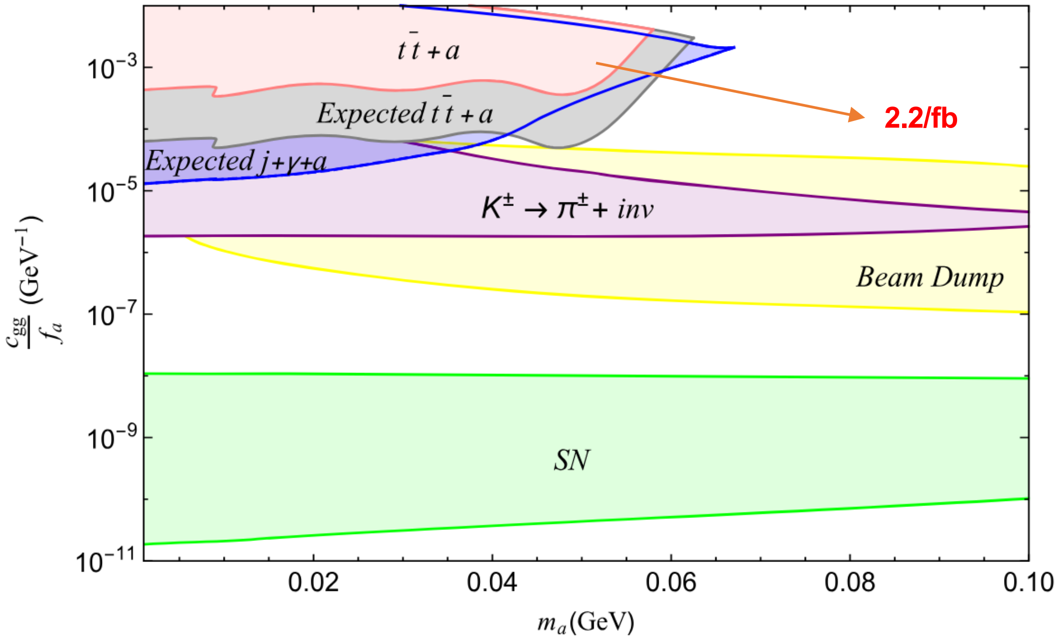
CHANNEL 3: Reinterpreting CMS Semileptonic $t\bar{t}$ + DM to Constrain $t\bar{t}$ + a

- **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.**

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

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

Phys. Rev. D 100, 015016 (2019)



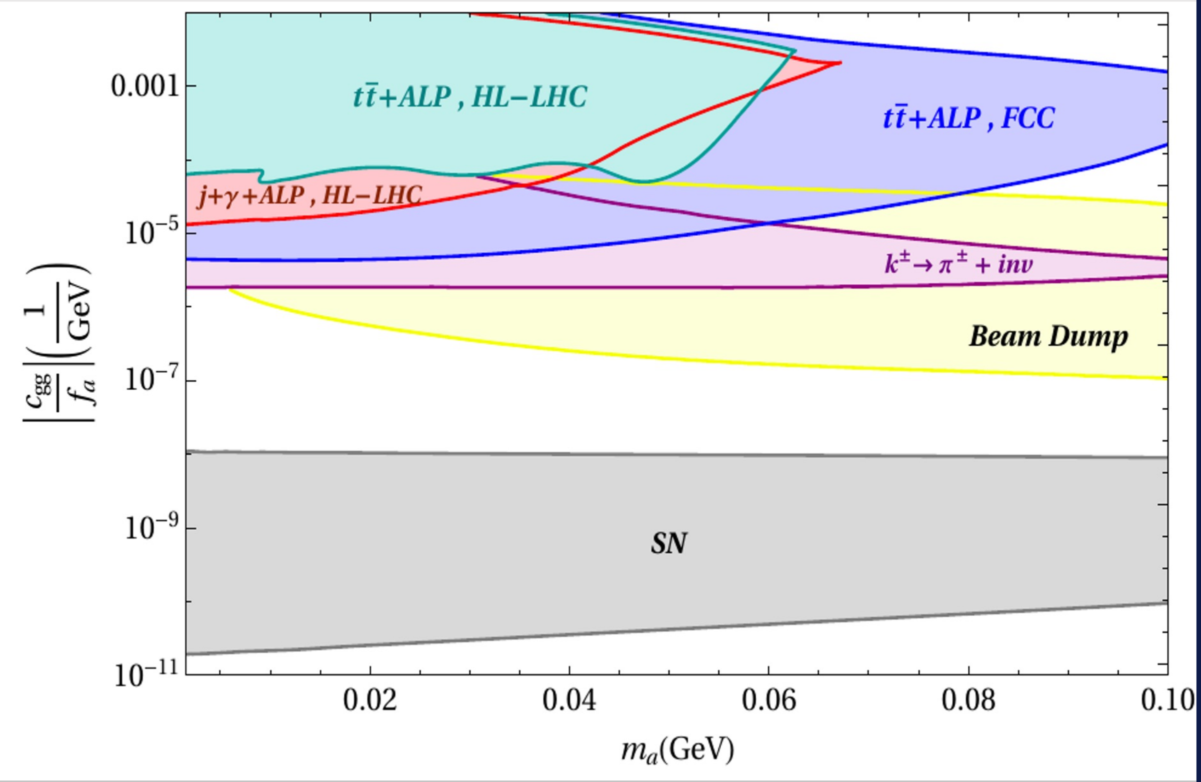
Event Selections:

- 1 isolated lepton, p_T ≥ 30 GeV, |η| < 2.5; extra-lepton veto
- ≥ 3 jets (≥1 b-tag), p_T ≥ 30 GeV, |η| ≤ 2.4
- E_T^miss ≥ 160 GeV and M_T ≥ 160 GeV
- H_T^miss ≥ 120 GeV and M_T2^W ≥ 200 GeV ($\bar{t}$t suppression)

- 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.

CHANNEL 3: $t\bar{t}$ + MET to constrain $t\bar{t}$ + a @ FCC-hh

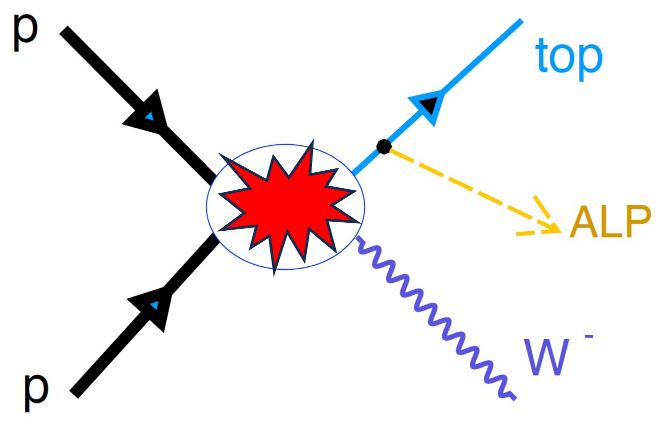
- At FCC-hh, hard ALP radiation becomes much more probable due to higher center-of-mass energy → strong sensitivity in the high-MET tail.
- The $1/p^3_{T,a}$ suppression is mitigated by the vastly increased phase space at FCC.
- **The FCC-hh analysis shows that a 100 TeV collider can probe ALP–gluon couplings down to $10^{-7,-6}$ 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.



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

CHANNEL 4

Precision ALP Probes: Unfolded Top-Quark Measurements (Ch. 5)



tt̄ Spin Correlations + a

- $\Delta\phi(e,\mu)$ dilepton azimuthal separation in tt̄ events
- ALP radiation distorts spin-correlation structure via recoil
- Orthogonal to traditional MET-based searches
- CMS 35.9 fb^{-1} unfolded: first spin-correlation ALP probe

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

Probing couplings to:
→ **Top quarks,**
→ **W bosons,**
→ **Gluons.**

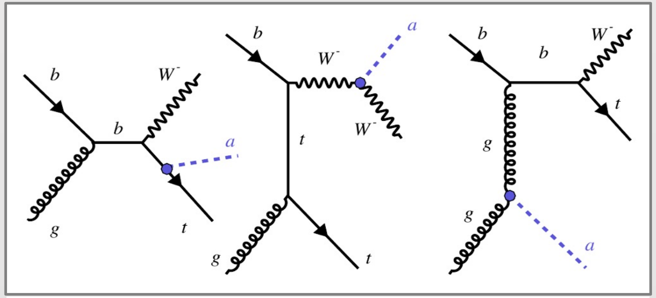
- We search for ALPs produced through the tW + a process at the LHC, using a reinterpretation of the CMS differential cross-section measurements for the tW production mode in pp collisions (JHEP07(2023)046: Run 2, 13 TeV).

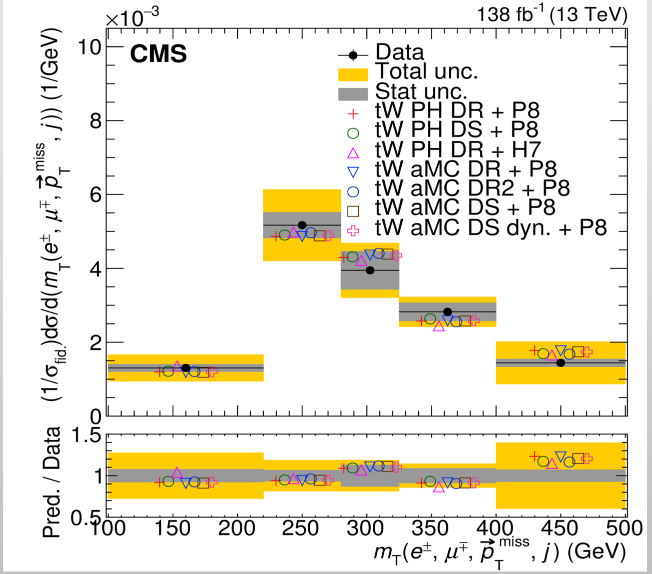
- The analysis focuses on the opposite-sign, different-flavor dilepton final state: $e^{\pm}\mu^{\mp}$ which provides a clean experimental signature with reduced background contamination.

➢ 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.

Physical Review D 110, 055026 (2024)





JHEP07(2023)046

CHANNEL 4 - ALP Production in the tW + a Channel

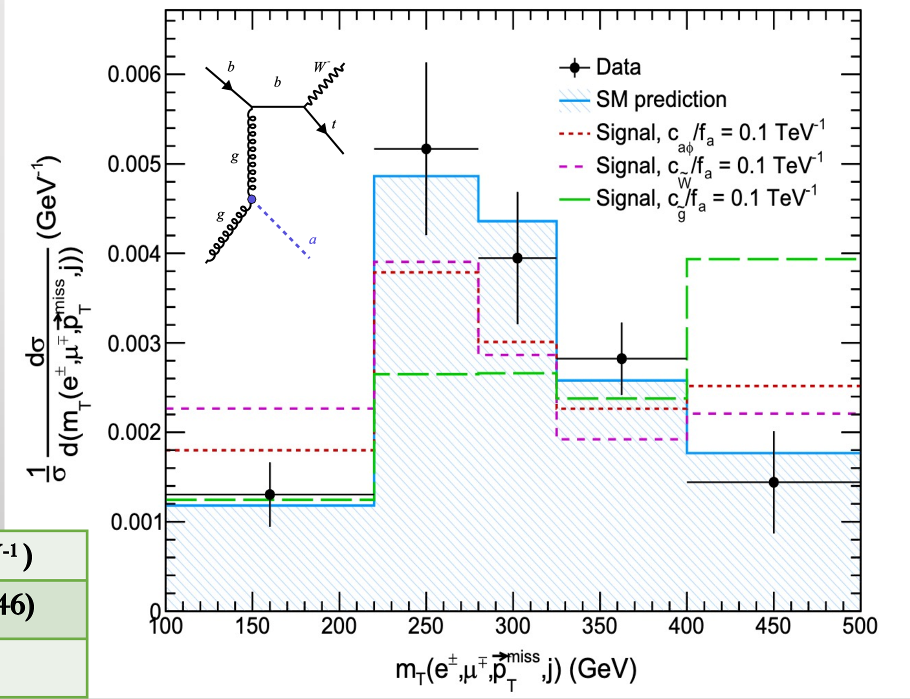
The ALP modifies the m_T distribution of the tW system through its couplings to the top quark, W boson, and gluons.

- 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:

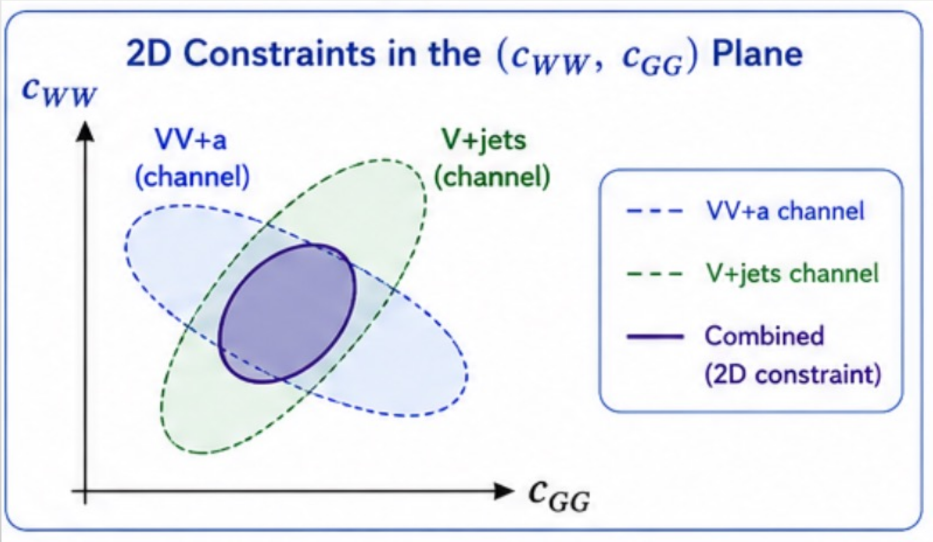
IL	c_t (GeV^{-1})	c_{GG} (GeV^{-1})	c_{WW} (GeV^{-1})
Run II – 139 fb^{-1}	0.016 (0.500)	0.003 (0.097)	0.008 (0.246)
HL-LHC – 3 ab^{-1}	0.011	0.002	0.005

Physical Review D 110, 055026 (2024)

Will be improved with more data

Concurrent ALP–gauge boson interactions: VVa + V+jets 2D limits

- **Resolve parameter degeneracies** arising from simultaneous ALP interactions.
- **Move beyond one-operator-at-a-time interpretations** toward a more realistic EFT framework.
- **Exploit complementary sensitivities** of electroweak (VV+a) and QCD (V+jets) production channels.
- **Obtain robust and correlated constraints** on the (c_{WW}, c_{GG}) parameter space.



ALP–Gauge Boson Interactions: 2D Constraints on (c_{WW}, c_{GG})

First concurrent probe of c_{WW}/fa AND c_{GG}/fa simultaneously

Two Complementary Strategies

Strategy A: VVa Production

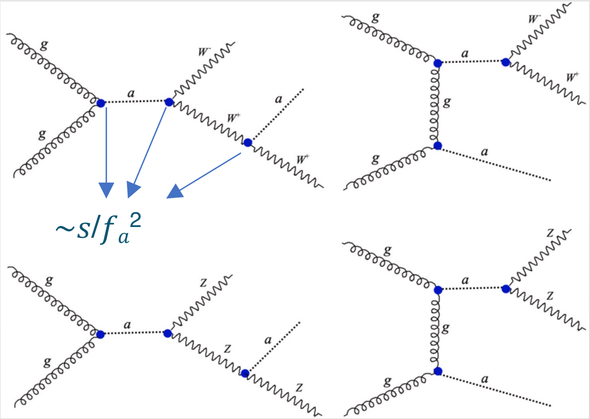
pp → ZZa (SR1: 4ℓ; SR2: 2ℓ+2j) and WWa (2ℓ)
Multiple EFT vertices; BDT on ETmiss, mZZ, ΔϕZZ
SR1 (fully leptonic ZZa) most sensitive: SM ZZ has negligible genuine MET
Results: 2D exclusion in (cWW, cGG) plane

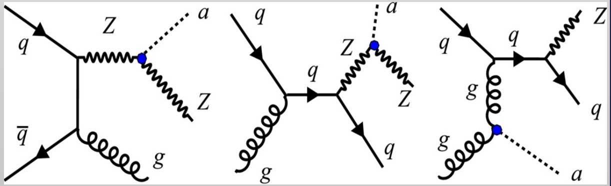
Strategy B: V+jets Unfolded

Reinterpret CMS Z+jets and W+jets differential data
High-pT tails enhanced by ALP radiation → χ^2 shape analysis
Z+jets > W+jets sensitivity at both couplings
Independent of detector-level systematics (uses unfolded data)

Channel
ZZa SR1 (4ℓ)
ZZa SR2 (2ℓ2j)
WWa (2ℓ)
Z+jets
W+jets

Feynman Diagrams





Highlight: First 2D (c_{WW}/fa, c_{GG}/fa) exclusion plane from multi-channel diboson + V+jets — model-independent concurrent constraints

Chenarani & MMN, Nucl. Phys. B 1018:116969 (2025)

VV+a Signal regions, MVA signal discrimination

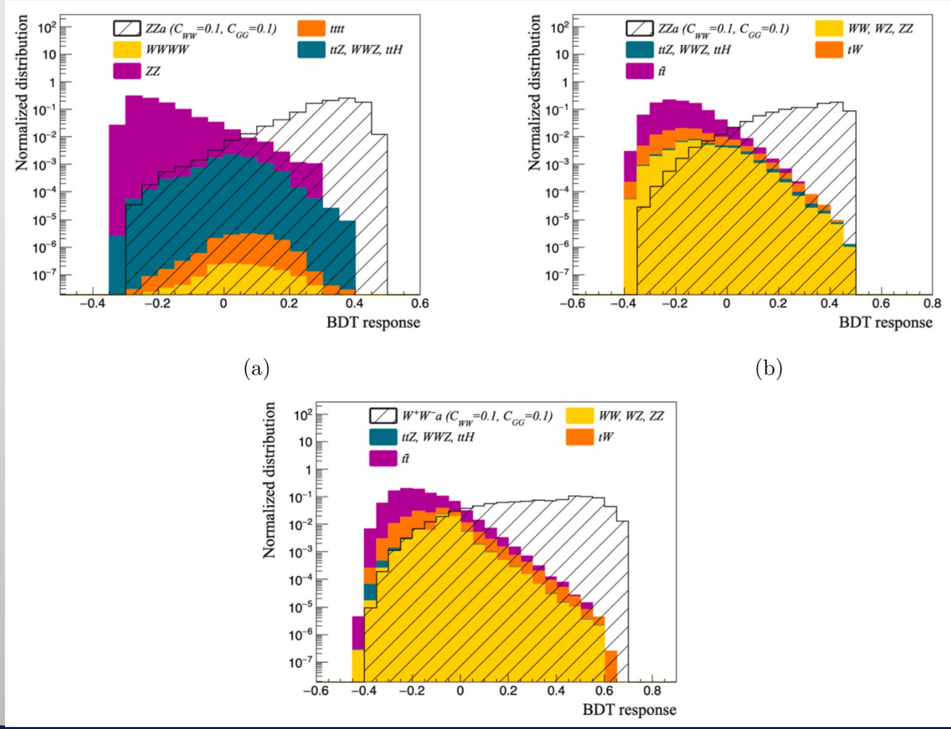
- ZZa SR1 — fully leptonic: 2 same-flavor OS lepton pairs (eeee,μμμμ,eeμμ), no jets, both pairs in the Z window
- ZZa SR2 — semi-leptonic: 1 same-flavor OS lepton pair + ≥ 2 jets, E_T^{miss} > 30 GeV
- WWa — fully leptonic: 2 OS leptons (any flavor combo), no jets, E_T^{miss} > 30 GeV

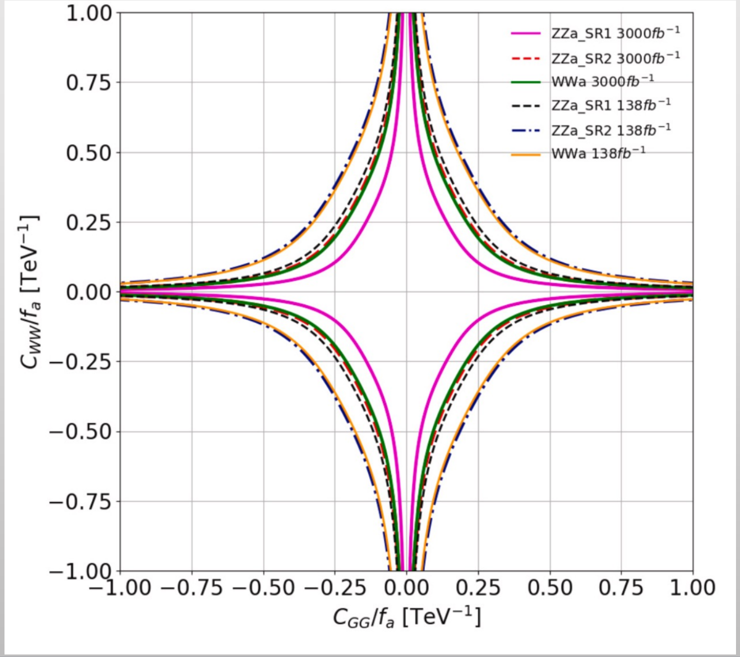
SR1 Input variables

- Missing transverse energy, E_T^{miss}
- Invariant mass of the 4 leptons, m_{ZZ}
- $|\sum p_T|$ of the 4 leptons, p_T^{ZZ}
- Azimuthal separation between the two Z's, $\Delta\Phi_{Z1Z2}$

SR2 Input variables

- Missing transverse energy, E_T^{miss}
- Invariant mass of the 2 leptons, $m_{\ell\ell}$
- $|\sum p_T|$ of the 2 leptons, $p_T^{\ell\ell}$
- ΔR between the two leptons, $\Delta R_{\ell 1 \ell 2}$
- Number of reconstructed jets, N_{jet}





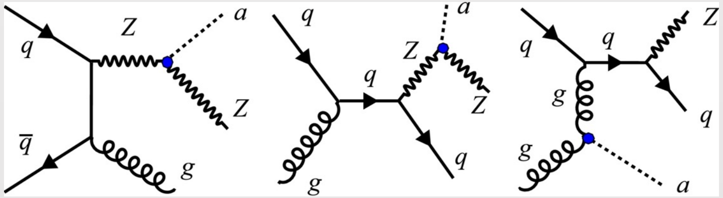
V + jet + a → V + jet +MET

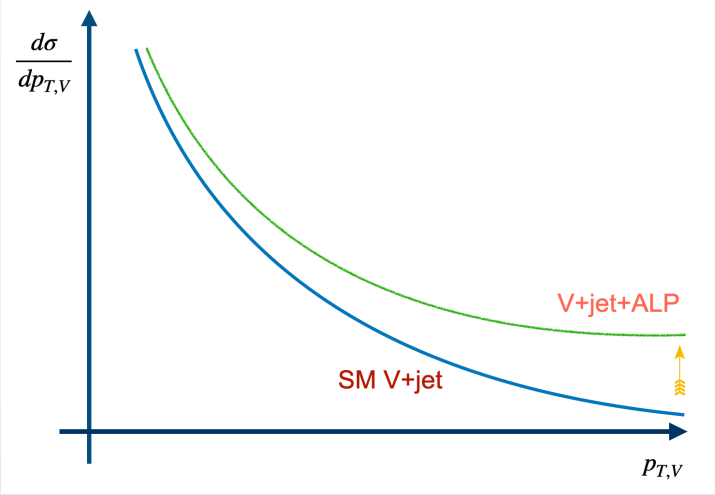
- These production channels are highly sensitive to the ALP couplings to gluons (c_G) and W bosons (c_W).

- ma = 1 MeV: Collider Stable --> V+jet +a similar signature as SM V+jet.

- In V+jets+a production, the dominant initial states are
  – quark–antiquark annihilation, and
  – gluon–quark interactions.
  – qg dominates: L_qg >> L_qqbar at LHC energies.

- The transverse momentum p_T of the vector boson (or the leading jet) is a crucial discriminator of the initial-state dynamics.





$$
\begin{cases}
Low - p_T: \dfrac{d\sigma}{dp_{T,V}} \propto \dfrac{1}{p_{T,V}} \, ln\left(\dfrac{m_V^2}{p_{T,V}^2}\right) \\
High - p_T: \dfrac{d\sigma}{dp_{T,V}} \propto \dfrac{1}{p^3{}_{T,V}} \left(1 + \mathcal{O}(\dfrac{m_V^2}{p_{T,V}^2})\right) \\
\textbf{Coupling Dependence}: \\
A \, (\dfrac{c_G}{f_a})^2 + B \cos^4\theta W (\dfrac{c_W}{f_a})^2 + C \cos^2\theta W \dfrac{c_W c_G}{f^2{}_a}
\end{cases}
$$

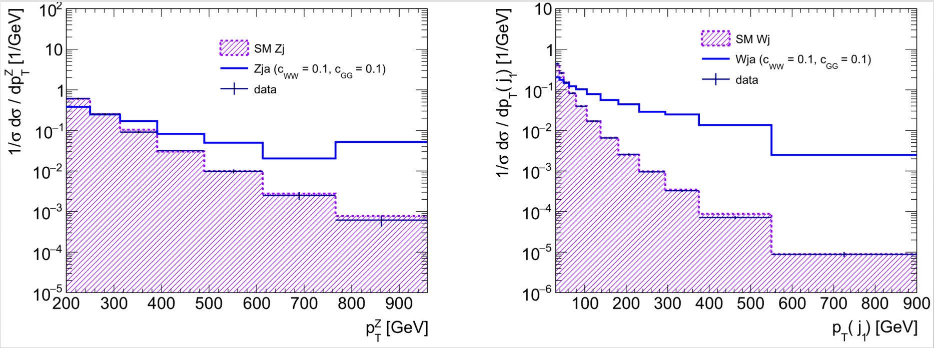
At high-energy:
- SM V+jet: Falls as $1/p_T^{\{4\text{-}5\}}$ (very steep)
- ALP V+jet +a: Falls as $1/p_T^3$ (less steep)
- ALP/SM ratio INCREASES with $p_{T,V}$

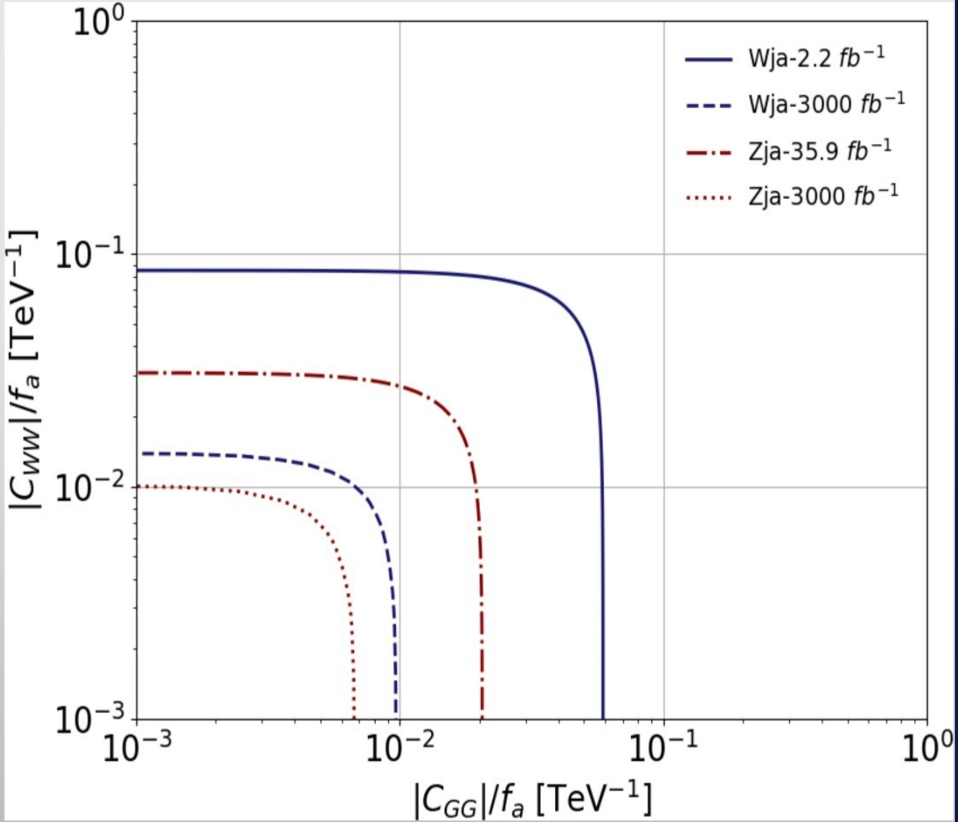
V + jet + a → V + jet +MET

To determine the upper limits on the couplings, the uncorrelated χ^2 functions of the ALP couplings and mass using the differential rates of $p_{T,Z}$ or $p_{T,j1}$.

The χ^2 function:

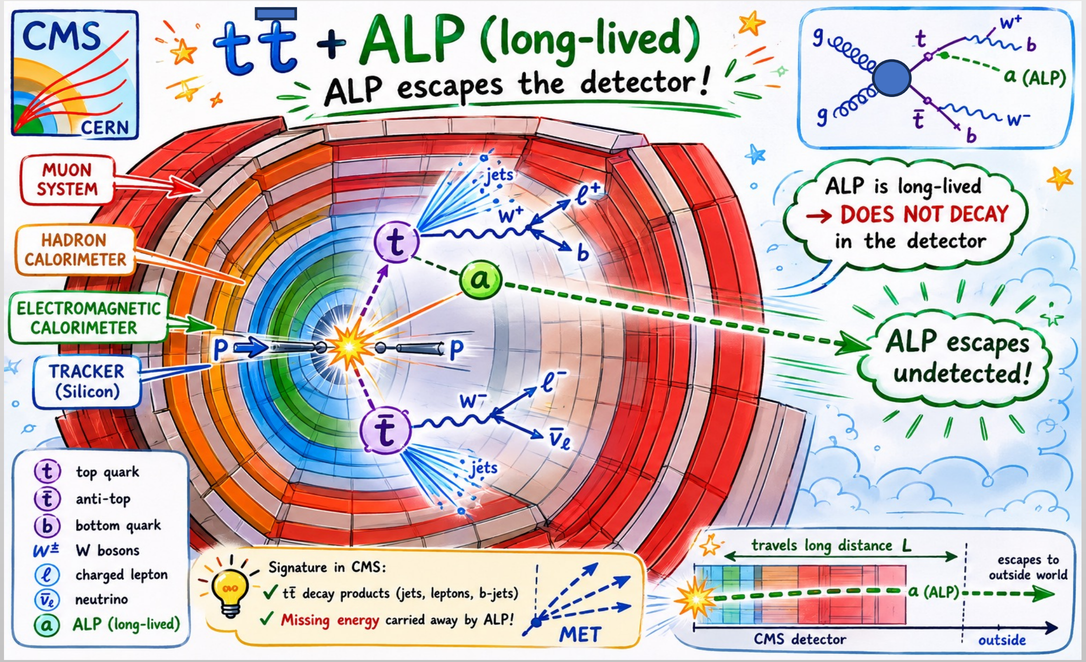
$$\chi^2\left(\frac{c_{WW}}{f_a}, \frac{c_{GG}}{f_a}, m_a\right) = \sum_{i \in \text{bins}} \frac{\left[\text{Data}(i) - \text{Bkg}(i) - \text{Pred}_{\text{ALP}}(i; \frac{c_{WW}}{f_a}, \frac{c_{GG}}{f_a}, m_a)\right]^2}{\delta_i^2}$$



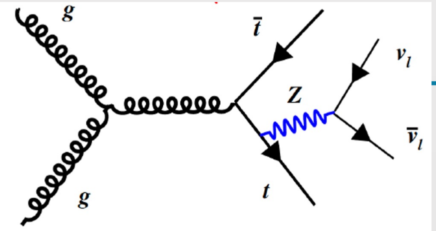


Experimental Realization at CMS

CMS Run 2 analysis — 138 fb^{-1} — direct constraints on ALP–top and ALP-gluon couplings



CMS Analysis: $t\bar{t}Z(Z\to\nu\bar{\nu}) \to t\bar{t} + a$ Reinterpretation (138 fb^{-1})



Full Run 2 dataset (2016–2018, 138 fb^{-1}, $\sqrt{s}$ = 13 TeV) — CMS collaboration internal analysis

Analysis Flow

1. **Data & MC Samples**
   2016+17+18; tt̄,WZ,ZZ,tt̄W,tt̄H backgrounds
   DY, fake-rate data-driven samples
2. **Object Reconstruction**
   e/μ (pT>20 GeV), AK4 jets, DeepCSV b-tag
   Particle-flow ETmiss, pileup mitigation
3. **Single-lepton SR**
   1ℓ+≥4j+≥2b+large ETmiss; 15-var BDT
   CR: nonprompt fake-rate application
4. **Dilepton SRs**
   ee,μμ (OSSF) and eμ (OF); BDT per SR
   tt̄ normalization CR; ZZ/WZ CRs
5. **ALP Reinterpretation**
   Signal reweighted: tt̄Z → tt̄+a (ma=1 MeV)
   Constraints on ct/fa and cGG/fa derived

Results & Systematics

Signal yields (1ℓ SR)

~15 expected tt̄Z signal events
S/B ~ 0.05–0.15 across BDT bins

Dominant experimental syst.

JES (±2–5%), b-tag (±3%), lumi (±1.6–2.5%)
Nonprompt lepton fake-rate (±15–25%)

Dominant modeling syst.

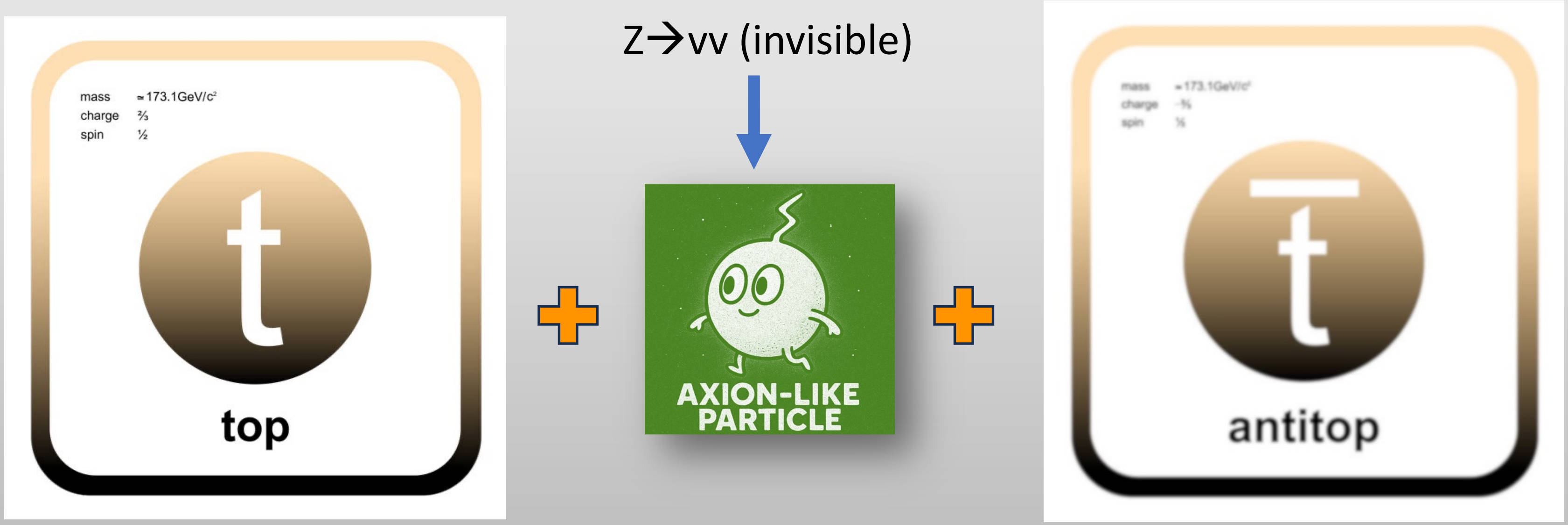
tt̄ normalization (from CR)
QCD scale, PDF, PS uncertainties

ALP coupling sensitivity

tt̄+a signal shape: harder ETmiss vs tt̄Z
Reinterpretation: first LHC limit on ct/fa and cGG/fa

Milestone: First direct constraint on ALP–top coupling from CMS Run 2 data — bridges my phenomenological program and real LHC data

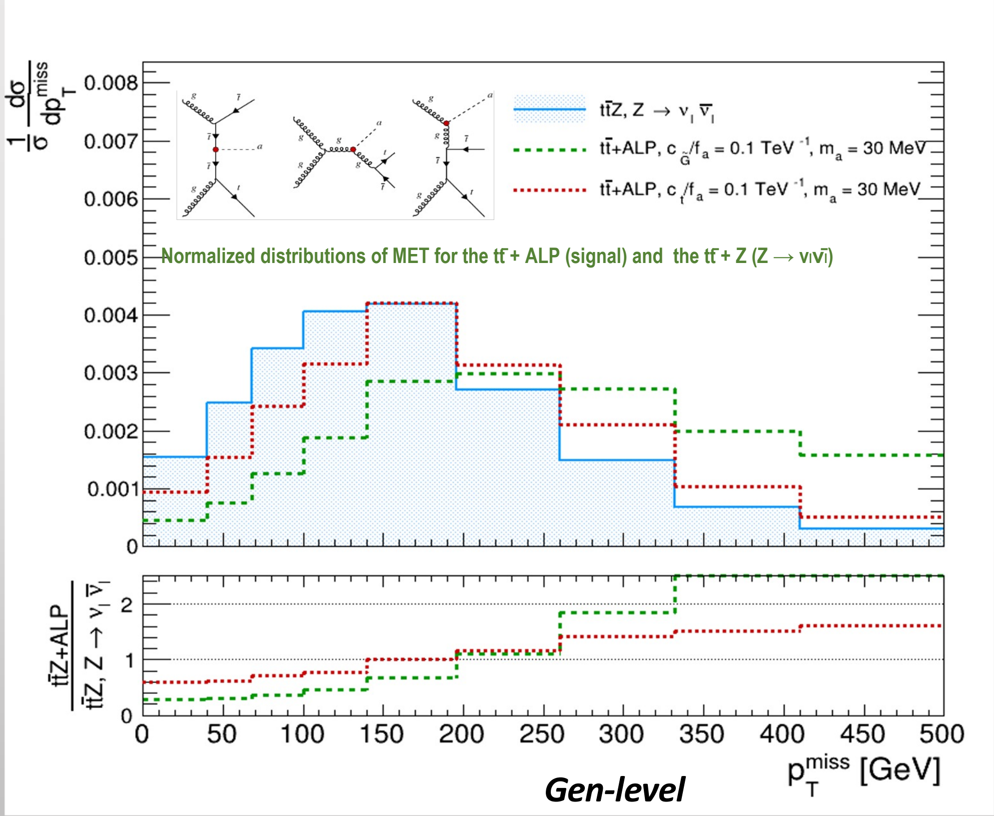
Ongoing Interpretation: $t\bar{t}$ + Z (→ Invisible) to Constrain $t\bar{t}$ + a



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 ($Z \rightarrow \nu_l\bar{\nu}_l$).
- The p_T^{miss} distribution reveals that the signal ($t\bar{t}$+ALP) and the background ($t\bar{t}$ + Z ($Z \rightarrow \nu_l\bar{\nu}_l$)) 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.

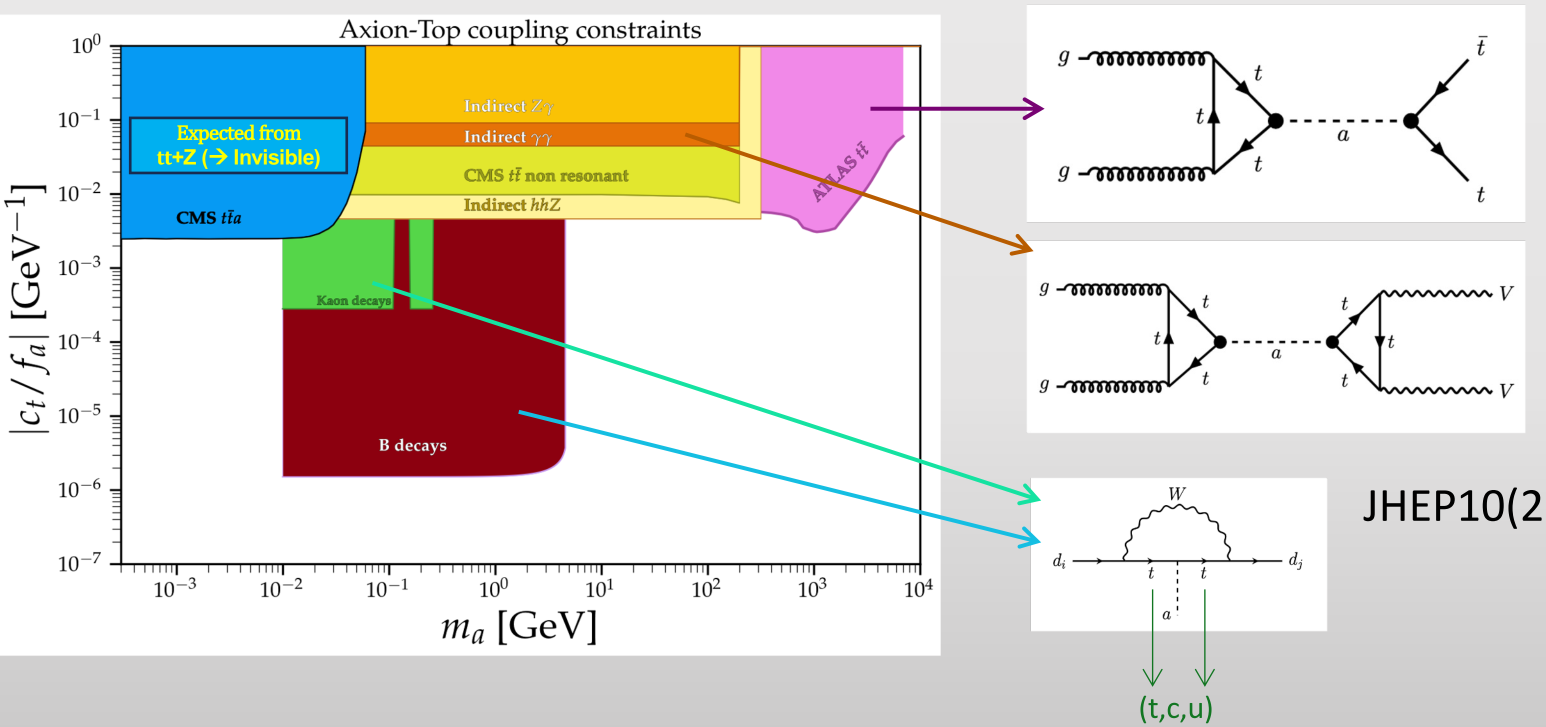
•We simulate the predicted yield of $t\bar{t}$ + a events in this region.

•To have a first rough estimation, we assume a 100% uncertainty on the fiducial $t\bar{t}$ + Z 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

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



JHEP10(2024)164

Analysis is going on → unblinding

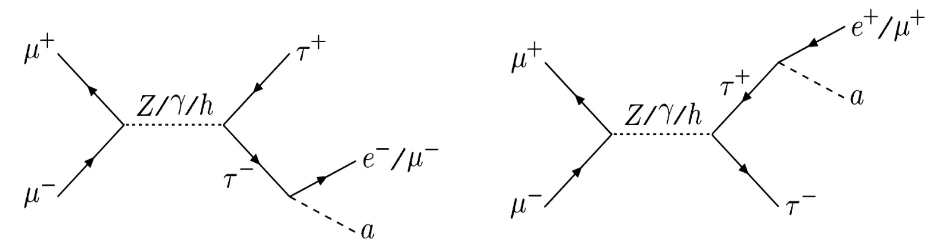
Part IV **Future Directions & Research Program**

Muon collider

Muon beams radiate ~10^9× less synchrotron power than electrons ($m_\mu/m_e \approx 207$) → circular acceleration is feasible. A 14 TeV muon collider reaches an effective energy similar to a 100 TeV FCC, with a cleaner environment than hadron colliders.

International Muon Collider Collaboration, coordinated largely through CERN with major contributions from Fermilab and many institutes worldwide. The 2020 European Strategy for Particle Physics recommended launching an international design study.

$$\sum_i \frac{\partial_\mu a}{2 f_a} \bar{\ell}_i c^A_{\ell_i \ell_i} \gamma^\mu \gamma_5 \ell_i + \sum_{i \neq j} \frac{\partial_\mu a}{2 f_a} \bar{\ell}_i \gamma^\mu (c^V_{\ell_i \ell_j} + c^A_{\ell_i \ell_j} \gamma_5) \ell_j$$

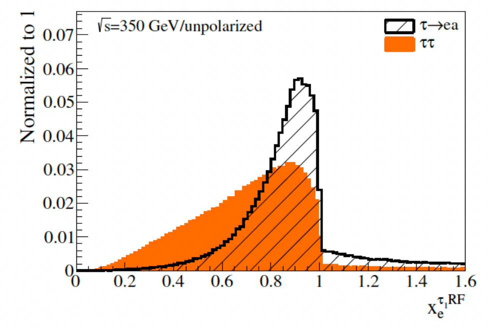


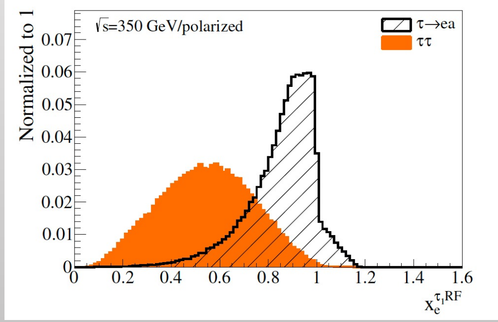
Phase	√s [GeV]	Avg. luminosity [10^{34} cm^{-2} s^{-1}]	Studied here
Higgs factory	126	0.008	✓
Top — high luminosity	350	0.6	✓
Multi-TeV (1st stage)	1500	1.25	✓
Multi-TeV	3000	4.4	—
Multi-TeV	6000	12	—

LFV ALPs at a Future Muon Collider: Polarization as a New Tool

New physics: LFV ALP coupling $c_{\tau e}$, $c_{\tau\mu}$ — off-diagonal, entirely untested. Signal: $\mu^-\mu^+ \to \tau^-\tau^+ \to (\ell+a)$(SM-decay)

- Signal kinematics: $\tau \to \ell a$ is a two-body decay → monoenergetic ℓ in τ rest frame
  - Key observable: $x_e^{\tau 1\text{-RF}} = E_e/E_e^{max}$ → signal peaks at exactly 1, SM $\tau \to \ell\nu\bar{\nu}$ is broad
- Background: SM $\tau^+\tau^-$ identical final state — the central challenge
- My innovation: Polarized muon beams (P=±0.8) shift τ helicity structure
  - SM $\tau+\tau-$ peak moves to low $x_e^{\tau 1\text{-RF}}$ — opens separation window with signal
  - LFV signal peak at $x_e^{\tau 1\text{-RF}}$ =1 unaffected by polarization → powerful discriminant
  - Reversed polarization (−0.8,+0.8) provides independent cross-check
- BDT combining $x_e^{\tau 1\text{-RF}}$, angular variables, deviation angles α_1, α_2

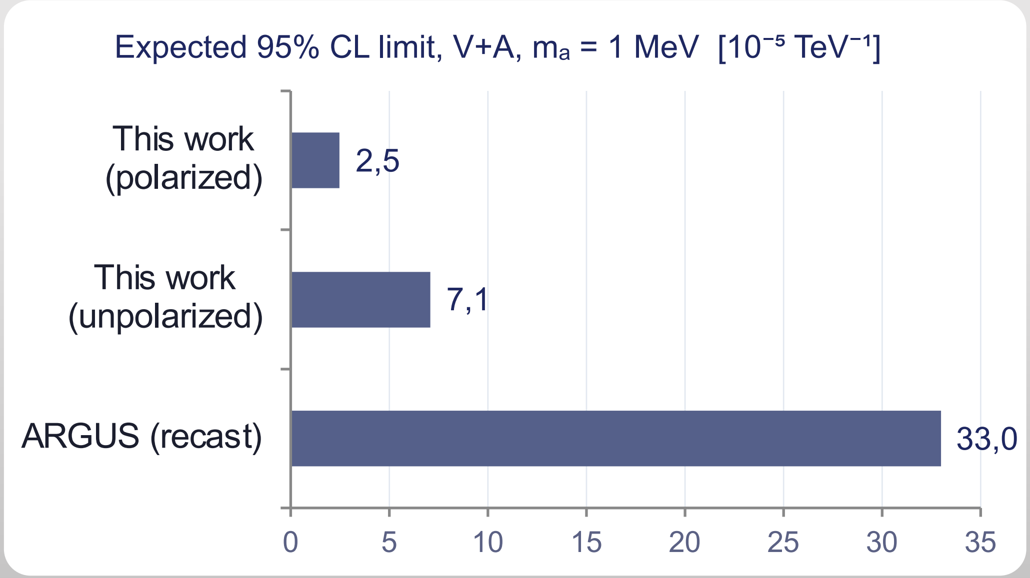




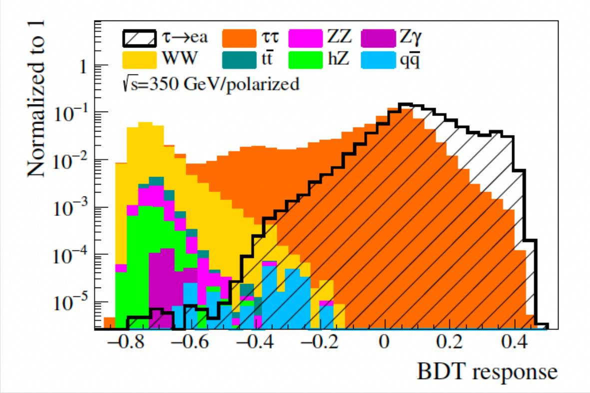
Reference: Haghighat & MMN, Nucl. Phys. B 980:115827 (2022)

LFV ALPs at a Future Muon Collider

Background → BDT discriminant → 8 kinematic variables incl. lepton energy fraction in the τ_1 rest frame



An order-of-magnitude improvement over ARGUS



Impact

- Beam polarization → necessary for sensitivity
- Muon collider unique window on LFV sector
- Current limits from LEP/B-factories: orders of magnitude weaker

Part IV

Future Directions & Research Program

ILC: Probing a Light Dark Sector

- SM Higgs doublet H
  - breaks SU(2)L × U(1)Y → VEV v = 246 GeV
- Dark Higgs singlet Φ
  - Breaks spontaneously G_{dark} → VEV v_Φ (free scale, 0.5–10 TeV) and NGB (ALP)
  - ALP acquires mass via explicit SB with renormalizable potential
- Portal coupling $\lambda_P\,|H|^2|\Phi|^2$
  - the only renormalizable bridge between the two sectors

λ_P induces mixing between the SM-like and dark Higgs bosons.

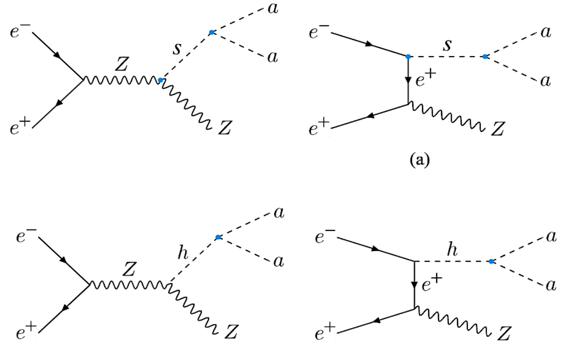
Free parameters:

Symmetry breaking scale v_Φ

m_a , m_s , mixing angle

Reference: Haghighat, MMN, Sakurai & Yin, PRD 107:035033 (2023)

Light Dark Sector via Invisible Higgs at ILC



Model: SM Higgs h + dark scalar s (Higgs portal); both h and s decay invisibly to ALP pairs aa → e^+e^- → (h/s)+Z → aa + Z(visible)

Seven Signal Regions (Z decay mode)

SR1: Z→e^+e^-	SR2: Z→$\mu^+\mu^-$
SR3: Z→$\tau^+\tau^-$(→e)	SR4: Z→$\tau^+\tau^-$(→μ)
SR5: Z→jj (light)	SR6: Z→jj (b-tag)
SR7: Z→$\nu\bar{\nu}$	

Key variable: mrecoil (peaks for h/s→aa)
cos Ω_{V1V2}, cos Ω_Z, cos $\Omega_{Z,s/h}$ → BDT

v_Φ (TeV)	0.5 ab^{-1}	2 ab^{-1}	HL-LHC
0.5	~0.08	~0.05	~0.25
1.0	~0.15	~0.10	~0.45
10.0	~0.40	~0.30	~0.80

Projected 95% CL Limits on sin α

ILC Advantage

- ILC (0.5 ab^{-1}) already surpasses HL-LHC for small v_Φ
- h and s contribute constructively: novel two-mediator interference
- Recoil-mass technique unique to lepton collider environment

Coherence of the Research Program: Full Coupling Coverage

Every ALP coupling probed; every collider environment covered; consistent EFT framework throughout:

Channels	c_{GG}/fa	c_{WW}/fa	c_t/fa	$c_{\tau\ell}/fa$	Higgs portal
dijet + E_{Tmiss}	●●●	○	○	—	—
γ+j + E_{Tmiss}	●●	●●●	○	—	—
$t\bar{t}$ + E_{Tmiss}	●●	○	●●●	—	—
tW+a / $t\bar{t}$ corr.	●●	●	●●	—	—
VVa (ZZa, WWa)	●●	●●●	○	—	—
V+jets unfolded	●●	●●	○	—	—
LFV muon coll.	—	—	—	●●●	—
ILC Higgs portal	—	—	—	—	●●●

●●● = primary ●● = medium ● = low ○ = loop/indirect — = not probed/not applicable

Collider Timeline

LHC Run 2/3
13–13.6TeV
138–300 fb^{-1}

HL-LHC
14 TeV
3 ab^{-1}

FCC-hh
100 TeV
30 ab^{-1}

Muon Coll.
126–1500 GeV
Staged

ILC
250 GeV
0.5–2 ab^{-1}

Future Research Program

Six research axes I will lead — combining expertise in EFT phenomenology, CMS experiment, and future collider design:

i Global EFT Combination

Simultaneous c_{GG}, c_{WW}, c_{BB}, ct, $c_{\tau\ell}$ fit
All channels in unified likelihood
Eliminate operator degeneracies

ii HL-LHC Run 3 Analyses

Signal-driven BDT optimization
Differential likelihood in 2D/3D spaces
Full CMS detector-level simulation

iii EFT Validity Treatment

Event-by-event reweighting $w=\min(1,fa^2/Q^2)$

Instead of a hard truncation → smoothly suppresses events as they approach or exceed the EFT validity limit.

iv Future Collider Program

Polarization at muon collider & ILC
Spin/angular operators discrimination
FCC-hh: 100 TeV parameter space map

v Cross-Collider Consistency

LHC + ILC + FCC + muon: consistent EFT
Coordinated interpretation frameworks

vi Supervision & Training

new PhD students planned (2027–29) !!!??

Conclusions

✓ Scientific Vision

Designed the first systematic multi-channel invisible-ALP collider program, spanning 4 experimental environments and multiple EFT operators

✓ Originality

First 2D concurrent coupling limits (cGG,cWW); first spin-correlation ALP probe; first LFV ALP study at muon collider with polarization

✓ Theory–Experiment Bridge

Conceived phenomenological strategy AND led its CMS experimental realization: first direct LHC limit on ALP–top coupling (138 fb^{-1})

✓ Independence & Leadership

7 papers in PRD/Nucl.Phys.B; 4 researchers (2 PhD + 2 postdoc) trained; CMS integration;

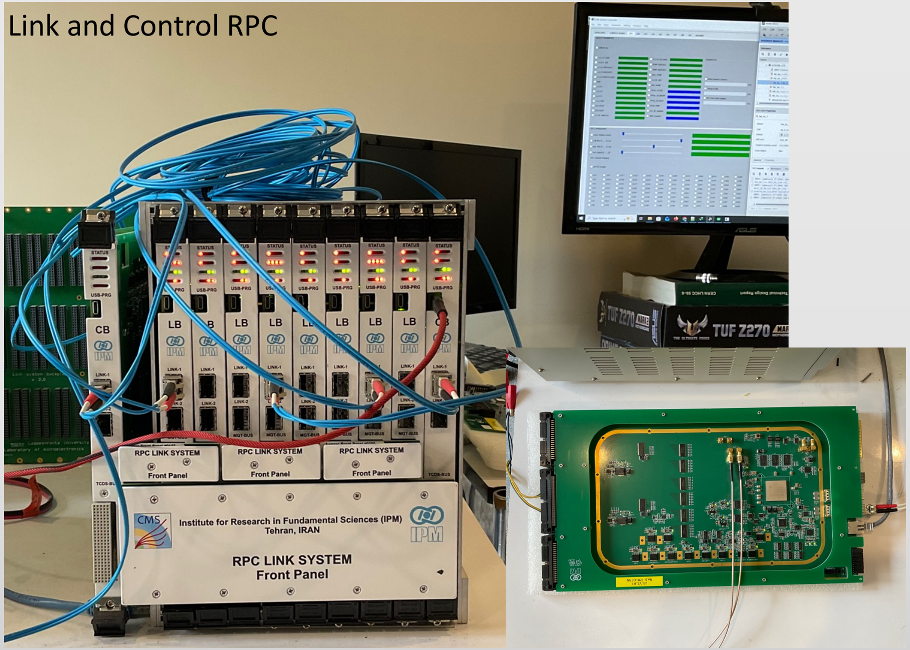
✓ Coherent Research Trajectory

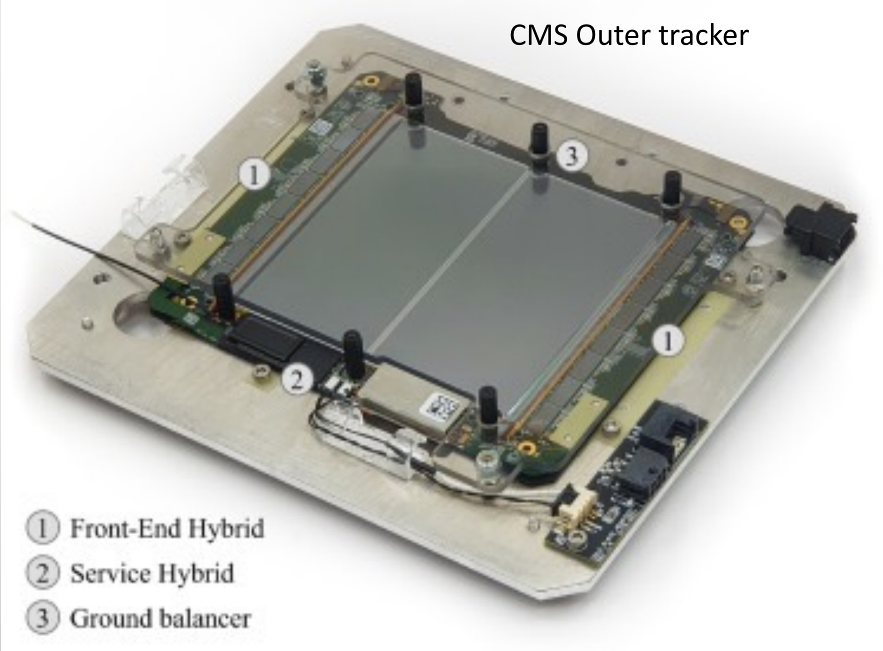
Progressive build-up: hadronic → top → gauge boson → precision → future colliders. Each step unlocks the next frontier

✓ Future Program

6 research axes for 2026–2030: global EFT, HL-LHC analyses, muon/ILC physics, cross-collider consistency, 2 new PhD students

CMS Phase-2: Recent Hardware activities





- IPM leadership, CMS LB RPC electronics upgrade
- **High-speed data transmission and monitoring of the RPC front-end electronics.**
- **Precise distribution of the LHC clock and trigger/control signals.**
- **Radiation-tolerant electronics for HL-LHC operation**
- **Complete electronic design and production coordination**
- 350 Ready to ship.

- Functional test of the hybrids
- bPOL studies these days, warm, cold 0 and 100% loads
- Wire bonding test, QC, etc

Leadership Roles & Awards

Leadership Roles

- Team leader, IPM CMS group (2016)
- Head of School of Particles & Accelerators, IPM (2017–2023)
- IPM Leadership in the CMS RPC Link & Control Board Project
- Established IPM–FCC collaboration partnership at CERN
- Established IPM–CEPC collaboration partnership at IHEP

Recognitions

- 🏆 IOP Outstanding Reviewer (2025)
- 🏆 IOP Trusted Reviewer (2024)
- 🥇 Best Young Scientist, NSF — $10,000 award (2018)
- 🥈 Young Khwarizmi Festival, 2nd rank (2008)
- 🏅 Young Researcher Award, Physical Society of Iran (2008)
- 📝 Referee: Phys. Lett. B, Reports Prog. Phys., J. Phys. G …

Thank You

Questions & Discussion

My sincere gratitude to the members of the jury for their time, evaluation, and participation in this HDR defense.

References: [1] PRD 100:015016 [2] PRD 102:115010 [3] Universe 8:301 [4] PRD 110:055026 [5] Nucl.Phys.B 1018:116969 [6] Nucl.Phys.B 980:115827 [7] PRD 107:035033

Backup

Simulation Setup for ttZ(→νν)

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.

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 MeV.

ALP Behaviours: Decay Probability

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

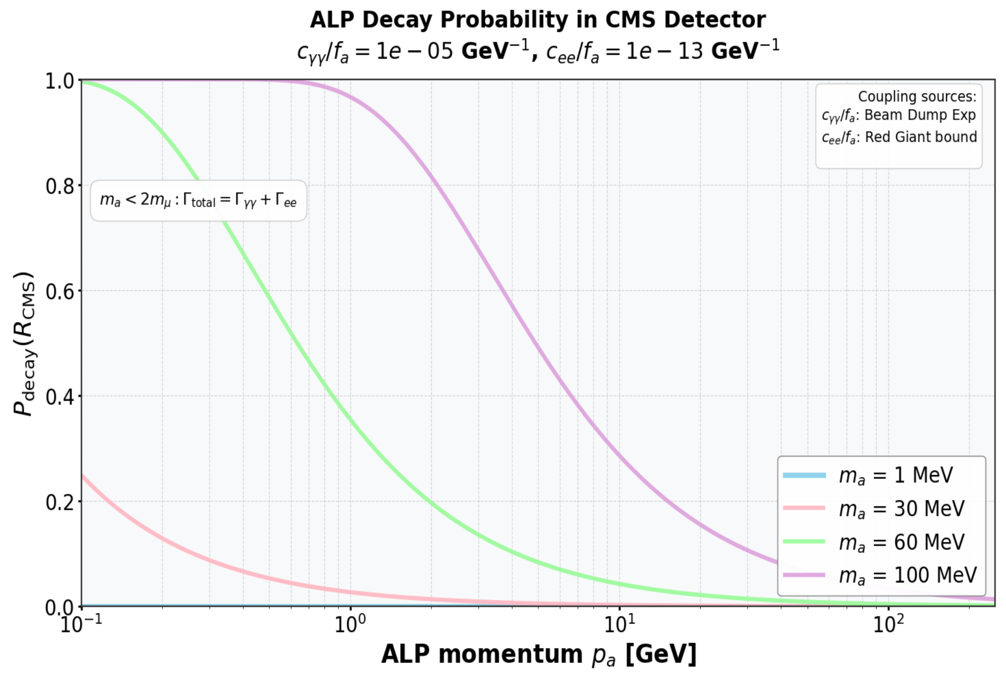
Transition from Collider Stable to Long-lived and Prompt.

-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