Exploring interference effects between two ALP effective operators at the LHC

卢致廷 Chih-Ting Lu ctlu@njnu.edu.cn

NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

2nd Topics of Particle, Astro and Cosmo Frontiers (TOPAC 2024)

Collaborators:
Kingman Cheung, C.J. Ouseph, Priyanka Sarmah

e-Print: 2404.14833 [hep-ph]

Probing the Top-Yukawa Coupling in Associated Higgs production with a Single Top Quark

#43

Jung Chang (Taiwan, Natl. Tsing Hua U.), Kingman Cheung (Taiwan, Natl. Tsing Hua U. and Konkuk U.), Jae Sik Lee (Chonnam Natl. U.), Chih-Ting Lu (Taiwan, Natl. Tsing Hua U.) (Mar 9, 2014)

Published in: *JHEP* 05 (2014) 062 • e-Print: 1403.2053 [hep-ph]

pdf DOI cite claim reference search 52 citations

Entangling Higgs production associated with a single top and a top-quark pair in the presence of anomalous top-Yukawa coupling

#39

Jung Chang (NCTS, Hsinchu), Kingman Cheung (NCTS, Hsinchu and Konkuk U. and Taiwan, Natl. Tsing Hua U.), Jae Sik Lee (Chonnam Natl. U. and NCTS, Hsinchu), Chih-Ting Lu (Taiwan, Natl. Tsing Hua U.) (Jul 22, 2016)

Published in: *JHEP* 04 (2017) 138 • e-Print: 1607.06566 [hep-ph]

pdf DOI cite claim reference search 6 citations

Contents

1. Motivation and Theoretical Setup

2. Production and Interference Effects in pp→ta+X

3. Experimental Setup and Numerical Results

4. Conclusion

Contents

Motivation of Axion-Like Partilces (ALPs)

1. **Strong CP problem (QCD axion)** Physics Reports 870 (2020), 1–117
2. **Ultralight dark matter & Small Scale Structure Problem**
3. **Experimental anomalies:** New J.Phys.11:105008,2009

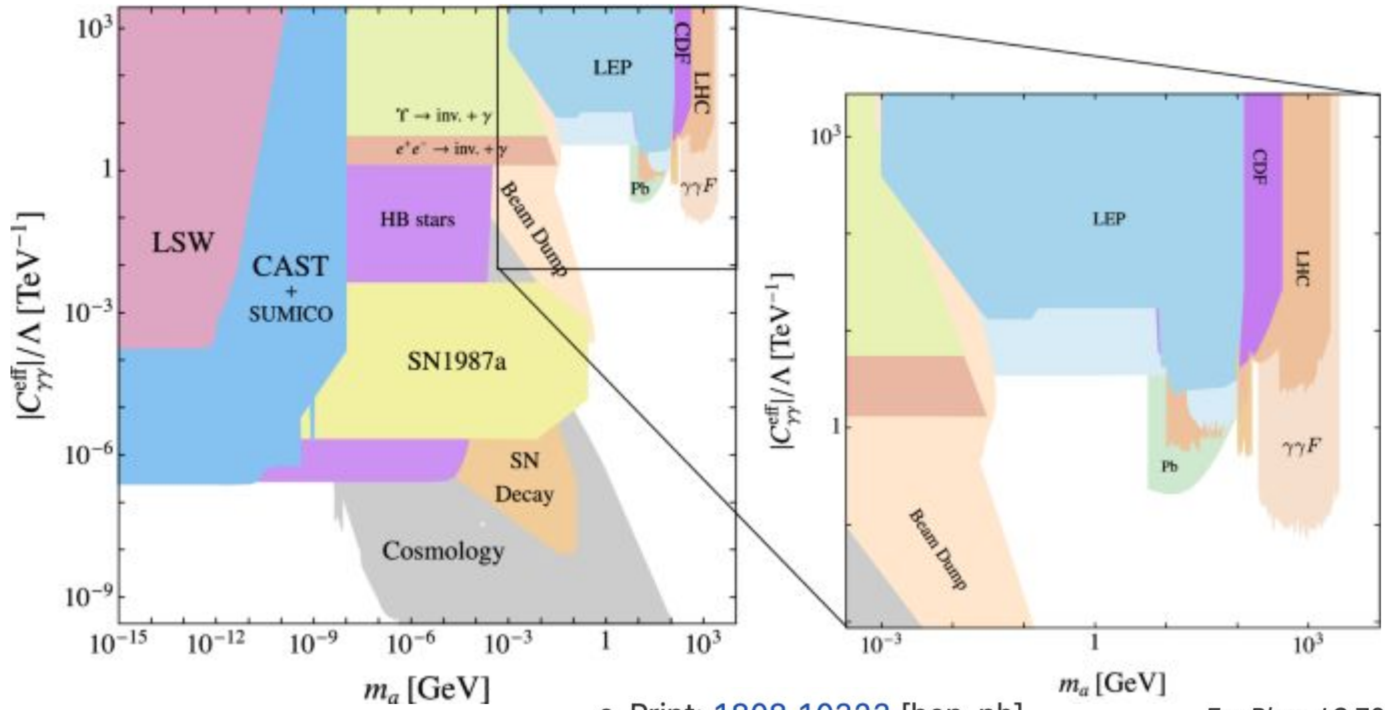
   (1) MiniBooNE Anomalous Excess Phys. Rev. D 104, 015030 (2021)

   (2) W Boson Mass Excess Sci.China Phys.Mech.Astron. 65 (2022) 12, 129512

   (3) Muon (g-2) Excess *Phys.Rev.D* 107 (2023) 9, 095016

   (4) Excess in $H \to Z\gamma$ e-Print: 2402.05678 [hep-ph]

Motivation of Axion-Like Partilces (ALPs)



e-Print: 1808.10323 [hep-ph]

Eur.Phys.J.C 79 (2019) 1, 74

Theoretical Setup

1. The CP-odd couplings of the ALP to the electroweak gauge boson fields:

ALP field (a)

$$\mathcal{L}_{\rm EW} \supset -\frac{a}{f_a}\left(C_{WW}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + C_{BB}B_{\mu\nu}\tilde{B}^{\mu\nu}\right),$$

ALP decay constant (f_a)

where i = 1, 2, 3 represents the SU(2) index.

2. After the spontaneous symmetry breaking, the above interactions can be written as

$$\mathcal{L}_{\rm EW} \supset -\frac{1}{4}a\left(g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{a\gamma Z}F_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aWW}W_{\mu\nu}\tilde{W}^{\mu\nu}\right),$$

Theoretical Setup

3. The dimensionful couplings of the photon and the electroweak gauge bosons to the ALP can be written in terms of C_{WW} and C_{BB}

$$g_{a\gamma\gamma} = \frac{4}{f_a}(C_{BB}c_w^2 + C_{WW}s_w^2), \qquad g_{aWW} = \frac{4}{f_a}C_{WW},$$

$$g_{aZ\gamma} = \frac{8}{f_a}s_w c_w(C_{WW} - C_{BB}), \quad g_{aZZ} = \frac{4}{f_a}(C_{BB}s_w^2 + C_{WW}c_w^2),$$

Theoretical Setup

4. The ALP-top quark pair interaction:

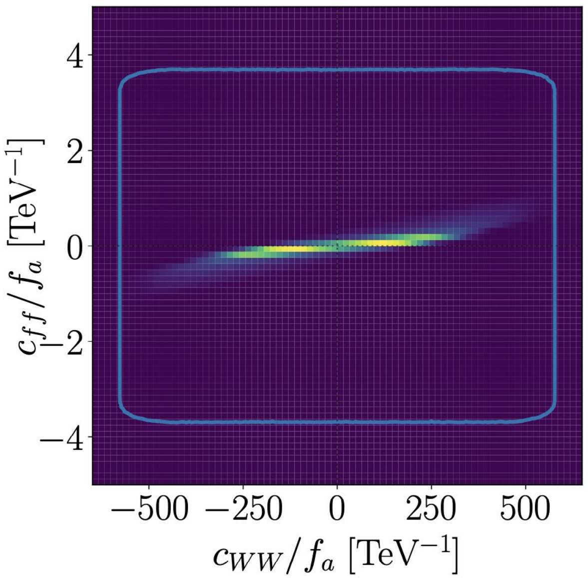
$$\mathcal{L}_{at\bar{t}} = C_{a\phi} \frac{\partial_\mu a}{2 f_a} (\bar{t} \gamma^\mu \gamma^5 t).$$

Apply the equation of motion

$$\mathcal{L}_{at\bar{t}} = -i C_{a\phi} \frac{m_t a}{f_a} (\bar{t} \gamma^5 t).$$

Motivation to study interference effects

1. We observe that most studies of ALP production channels at the LHC focus on a single type of ALP operator for each process in the EFT framework.
2. From the global analysis of the ALP EFT, people can study the constraints between two ALP effective operators.



Global analysis of the ALP effective theory

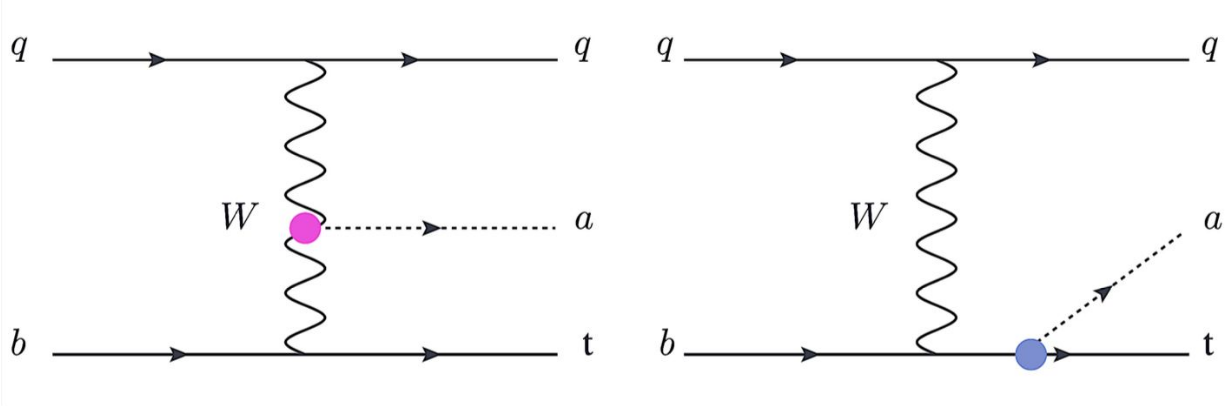
Sebastian Bruggisser (U. Heidelberg, ITP and Uppsala U.), Lara Grabitz (U. Heidelberg, ITP), Susanne Westhoff (U. Heidelberg, ITP and Nijmegen U., IMAPP and Nikhef, Amsterdam) (Aug 22, 2023)

Published in: *JHEP* 01 (2024) 092 • e-Print: 2308.11703 [hep-ph]

Motivation to study interference effects

3. The key point for this work is to study some specific processes which involves at least two types of relevant ALP effective operators together and their interference effects!

$$pp \to tja$$

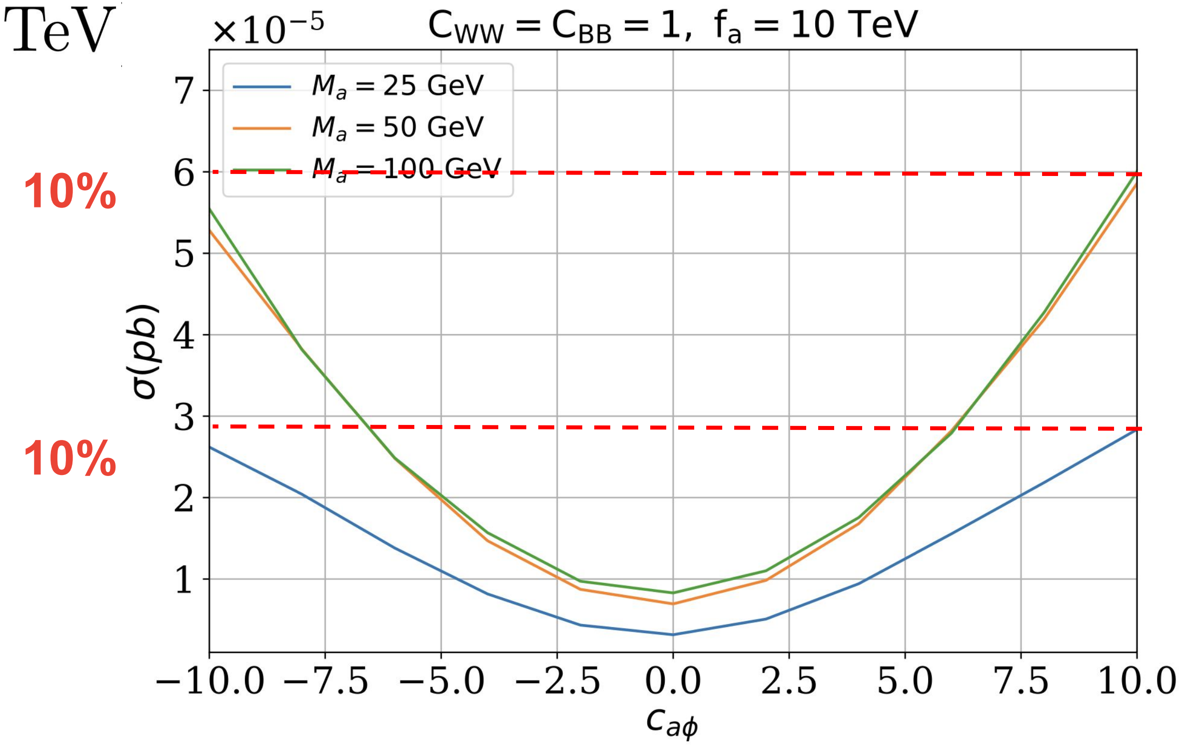


Contents

1. Motivation and Theoretical Setup
2. **Production and Interference Effects in pp→ta+X**
3. Experimental Setup and Numerical Results
4. Conclusion

$$pp \to j\ t\ a \text{ with } a \to \gamma\gamma \text{ and } t \to bW,\ W \to l\nu_l$$

$\sqrt{s} = 14$ TeV

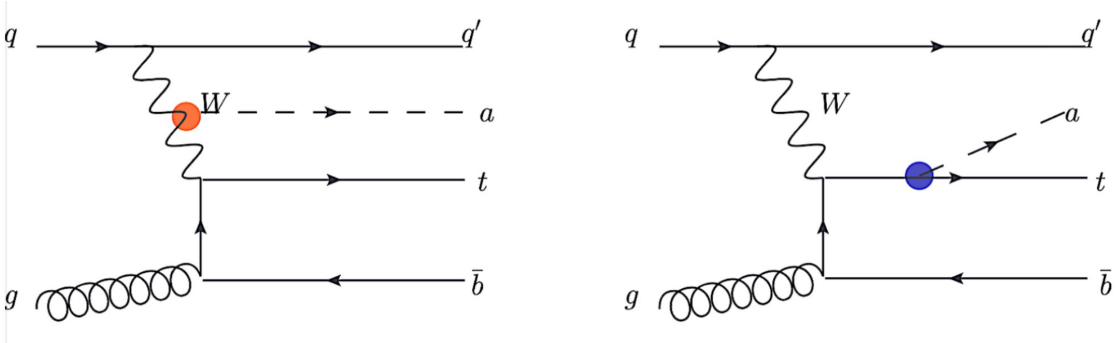


Other associated ALP production with a single top quark processes

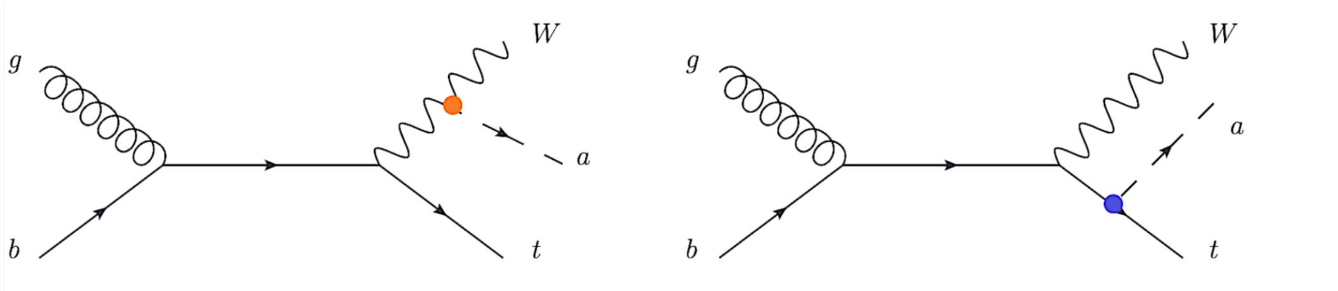
1. p p → t j b a
(1) This process can be regarded as a high-order correction from p p → t j a when the b-quark is not tagged in the final state.
(2) To identify this process from p p → t j a and avoid the collinear divergence, the following cuts are applied:

$$P_{T_b} > 25 \text{ GeV}, \quad |\eta_b| < 2.5, \quad P_{T_j} > 10 \text{ GeV}, \quad |\eta_j| < 5.$$

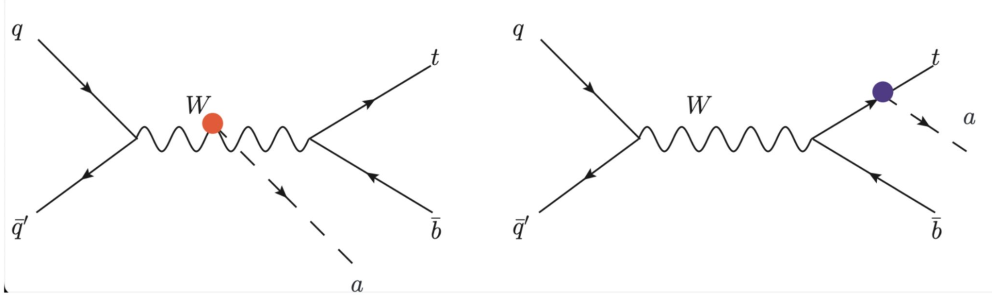
2. p p → t W a
3. p p → t b a



$$pp \to tjba$$

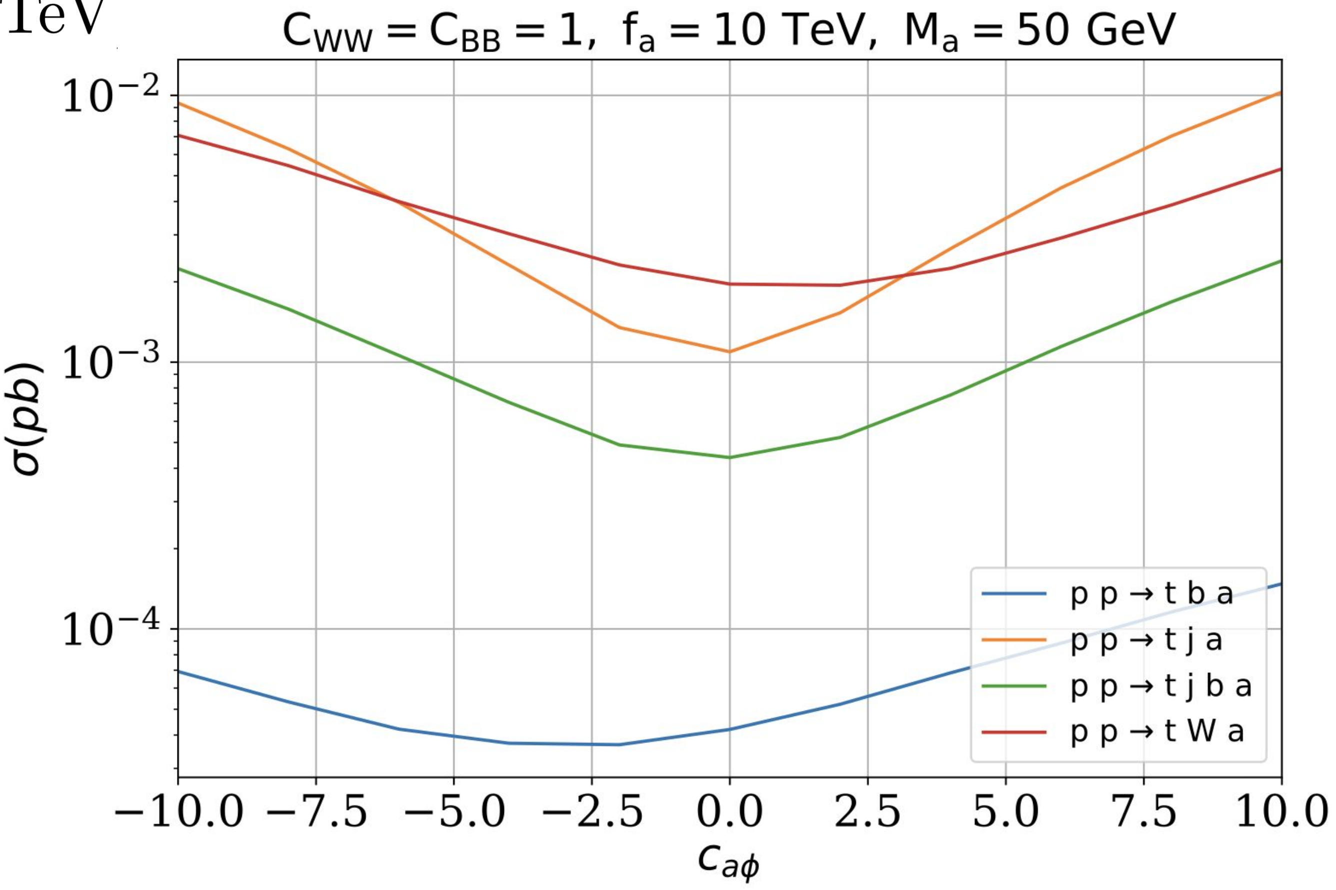


$$pp \to tWa$$



$$pp \to tba$$

$\sqrt{s} = 14$ TeV


$C_{WW} = C_{BB} = 1,\ f_a = 10$ TeV, $M_a = 50$ GeV
10^{-2}
10^{-3}
10^{-4}
$\sigma(pb)$
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
$c_{a\phi}$
p p → t b a
p p → t j a
p p → t j b a
p p → t W a

Contents

Simulation

Signal (p p → t j a):

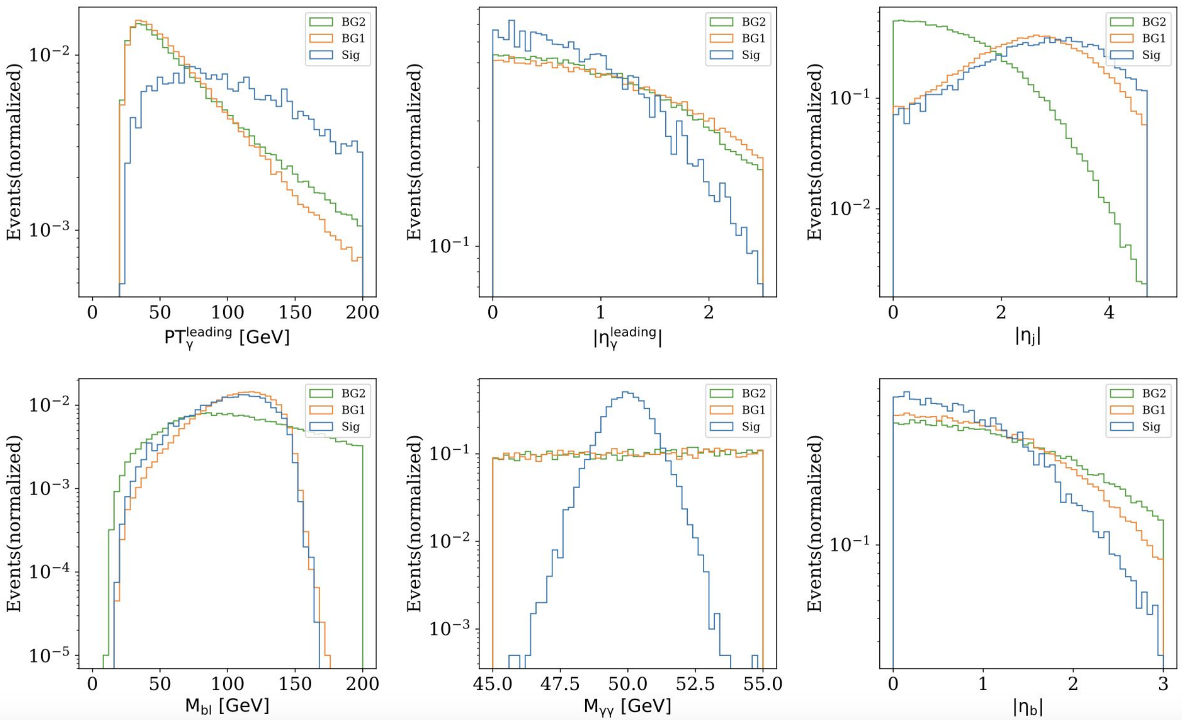
1. We focus on the ALP within a mass range from 25 GeV to 100 GeV such that the final-state signature is two isolated photons.
2. Fixing $f_a = 10$ TeV, $C_{WW} = C_{BB} = 1$, and a scan of $C_{a\phi}$ from -10 to 10.
3. Semi-leptonic decay of the top quark: $t \to Wb, \quad W \to l\nu_l$

Relevant SM backgrounds:

1. BG1: p p → t j γ γ (dominant)
2. BG2: p p → W j γ γ

Kinematical distributions

$M_a = 50$ GeV, $f_a = 10$ TeV, $C_{WW} = C_{BB} = 1$, $C_{a\phi} = 10$



Cuts for the signal and background event selections:

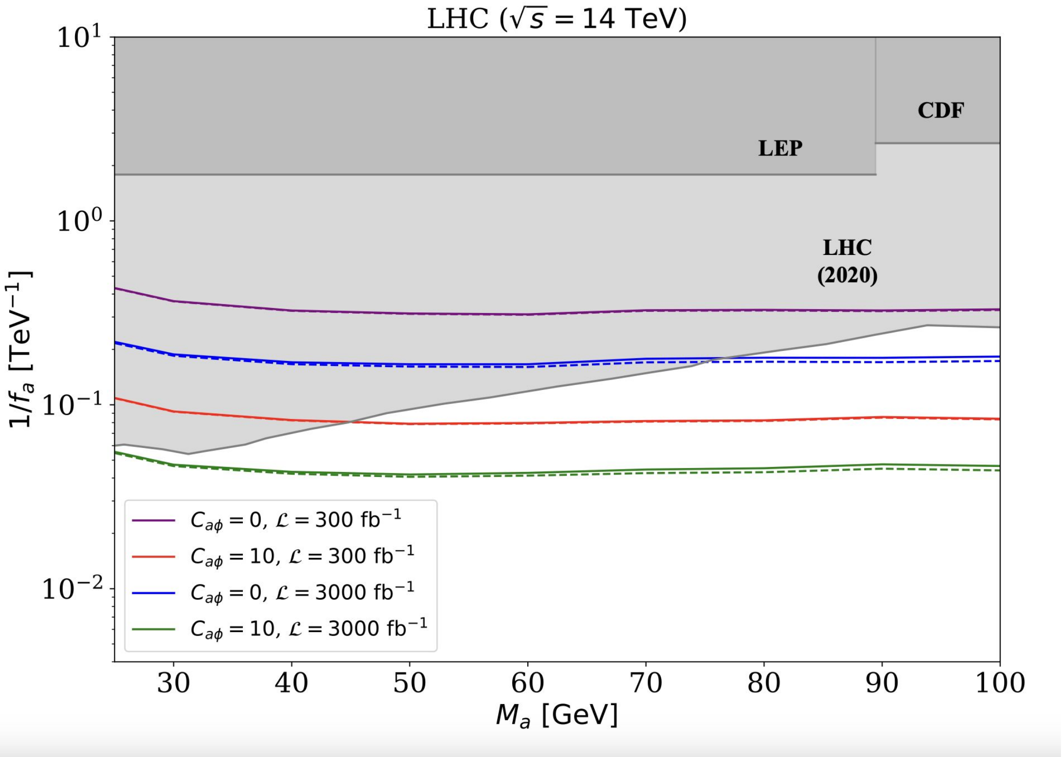
- $P_{T_\gamma}^{\text{leading}} > 60$ GeV,
- $|\eta_\gamma^{\text{leading}}| < 1.5$,
- $2.5 < |\eta_j| < 4.7$,
- $M_{bl} < 200$ GeV,
- $|\eta_b| < 1.5$,
- $|M_{\gamma\gamma} - M_a| < 5$ GeV.

$$M_a = 50\ GeV,\ f_a = 10\ TeV,\ C_{WW} = C_{BB} = 1 \qquad \mathcal{L} = 3000\ \text{fb}^{-1}$$

Cut	**BG1**	**BG2**	**Signal**				
			$C_{a\phi} = -10$	$C_{a\phi} = -5$	$C_{a\phi} = 0$	$C_{a\phi} = 5$	$C_{a\phi} = 10$
NT	2318.39	307.86	120.56	43.26	15.73	49.69	131.68
$P_{T_\gamma}^{\text{leading}} > 60$ GeV	1181.01	170.03	99.22	36.80	14.83	42.53	109.11
$\lvert\eta_\gamma^{\text{leading}}\rvert < 1.5$	853.03	124.99	81.24	29.35	10.90	33.61	88.86
$2.5 < \lvert\eta_j\rvert < 4.7$	384.44	8.92	47.97	15.80	3.45	17.05	51.62
$M_{bl} < 200$ GeV	384.44	7.03	47.97	15.80	3.45	17.05	51.62
$\lvert\eta_b\rvert < 1.5$	266.20	4.68	37.94	12.38	2.56	13.47	40.46
45 GeV $< \text{M}_{\gamma\gamma} <$ 55 GeV	8.95	0.15	37.94	12.38	2.56	13.47	40.46

Exclusion regions at 95% C.L.

$$C_{WW} = C_{BB} = 1$$



Solid lines:
10% systematic uncertainties
Dashed lines:
no systematic uncertainties

Contents

Conclusion

- We demonstrated the interference effects of the ALP-gauge boson pair and the ALP-top quark pair couplings in the process p p → t j a.

- Our findings indicate that the sensitivity of the ALP cutoff scale f_a could potentially reach down to the values around $1/f_a \sim 5 \times 10^{-2}\ \mathrm{TeV}^{-1}$ for the ALP masses ranging from 25 GeV to 100 GeV at the HL-LHC.

- It's important to find more novel processes which can explore interference effects between two or more ALP effective operators!

Thank you

for your attention