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Probing the Gauge-boson Couplings of Axion-like Particle at the LHC

Based on: JHEP 05 (2024) 324

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Outline

- Introduction to ALP
- Simulation and Selection Method
- Numerical Result
- Summary

Introduction to ALP

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Introduction to ALP

- Axion is proposed to solve the strong CP problem

> **7. Conclusion**
>
> But then again, maybe the axion doesn’t exist.

Credit: Ciaran A.J. O'Hare, “Cosmology of axion dark matter”, PoS COSMICWISPers (2024), 040

- ALP stands for axion-like particle
- ALP is a dark matter candidate.
- The mass range of ALP could be very wide.
- ALP is constrained by cosmology, astronomy and collider experiments.

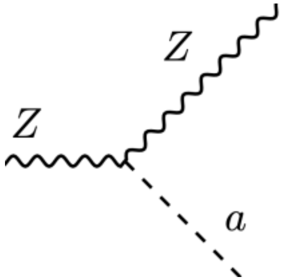
The ALP Model

- The interaction Lagrangian:

$$\mathcal{L}_{ALP} = \mathcal{L}_f + \mathcal{L}_g - \frac{a}{f_a}\Big[C_{ww} W^{+}_{\mu\nu} \widetilde{W}^{-\mu\nu} + (C_{BB} {c_w}^2 + C_{WW} {s_w}^2) F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ (C_{BB} {s_w}^2 + C_{WW} {c_w}^2) Z_{\mu\nu} \tilde{Z}^{\mu\nu} + 2(C_{WW} - C_{BB}) c_w s_w F_{\mu\nu} \tilde{Z}^{\mu\nu}\Big]$$

- The ALP-gauge boson couplings:

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



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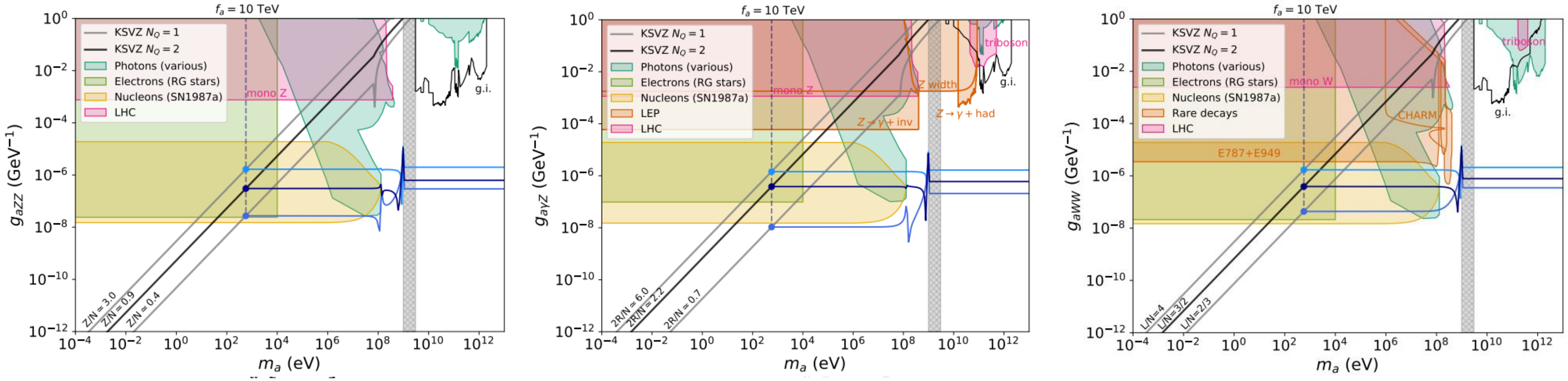
Current Limit of ALP coupling

- In my study, we focus on the couplings g_{aZZ} and $g_{aZ\gamma}$ with the mass range $1\ GeV \ \le M_a \le 100\ GeV$.
- Most of the constraints are given by collider experiment in this mass range
- $g_{aZZ}, g_{aZ\gamma}$ can be transferred from $g_{a\gamma\gamma}$ by choosing C_{WW}, C_{BB}.
  - $g_{aZZ} = \frac{4}{f_a}(C_{BB}{s_w}^2 + C_{WW}{c_w}^2)$ $\quad g_{aZ\gamma} = \frac{8}{f_a}(C_{WW} - C_{BB})c_w s_w$
    $g_{a\gamma\gamma} = \frac{4}{f_a}(C_{BB}{c_w}^2 + C_{WW}{s_w}^2)$

Current Limit of ALP coupling



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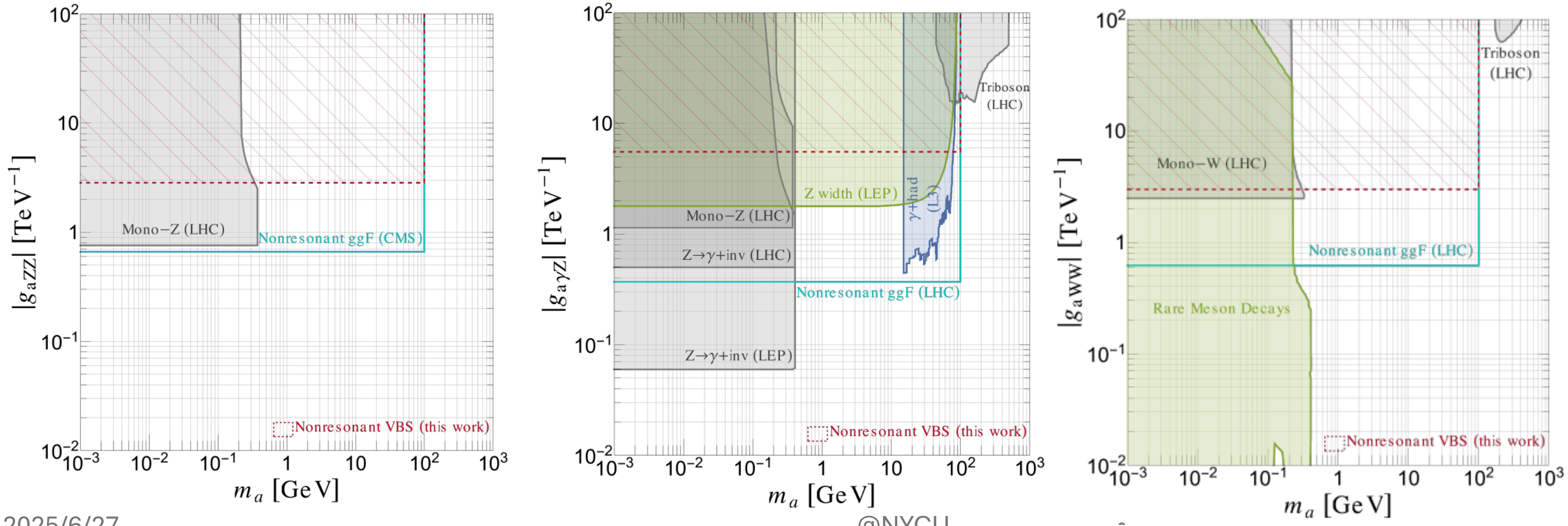

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Simulation and Selection Method

Simulation Method

- Center-of-mass energy $\sqrt{s} = 14\,TeV$
- Model: FeynRules (with ALP Lagrangian)
- Parton-level: MadGraph5_aMC@NLO
- Showering: Pythia8 (with default setting)
- Detector: Delphes3 (with ATLAS card)

Signal Events (Z channel)

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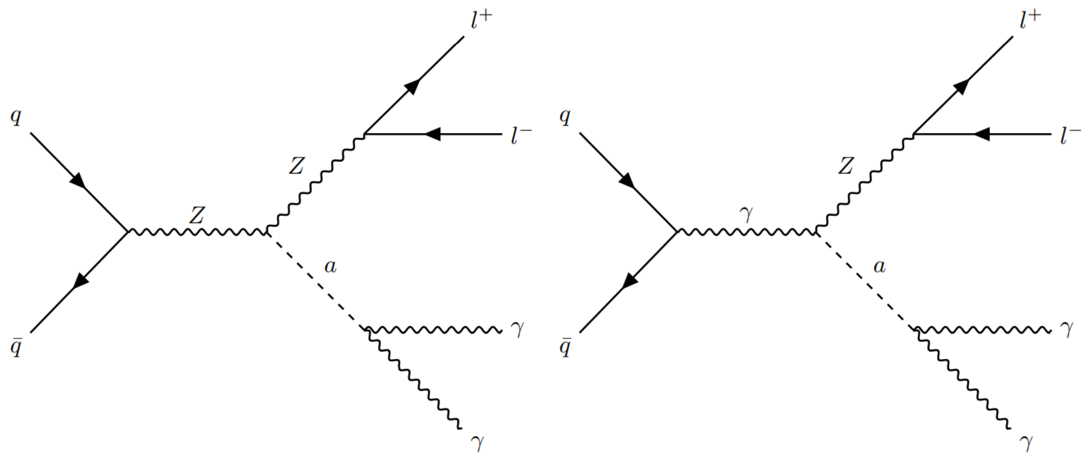
- $pp \to Za(Z \to l^+l^-)(a \to \gamma\gamma)$
- $1\ GeV \ \le M_a \le 100\ GeV$
- 10^4 events for each ALP mass
- Benchmark value:
  - $f_a = 1\ TeV$
  - $C_{WW} = 2$
  - $C_{BB} = 1$
  - No fermion and gluon couplings
  - Decay width is set to be auto

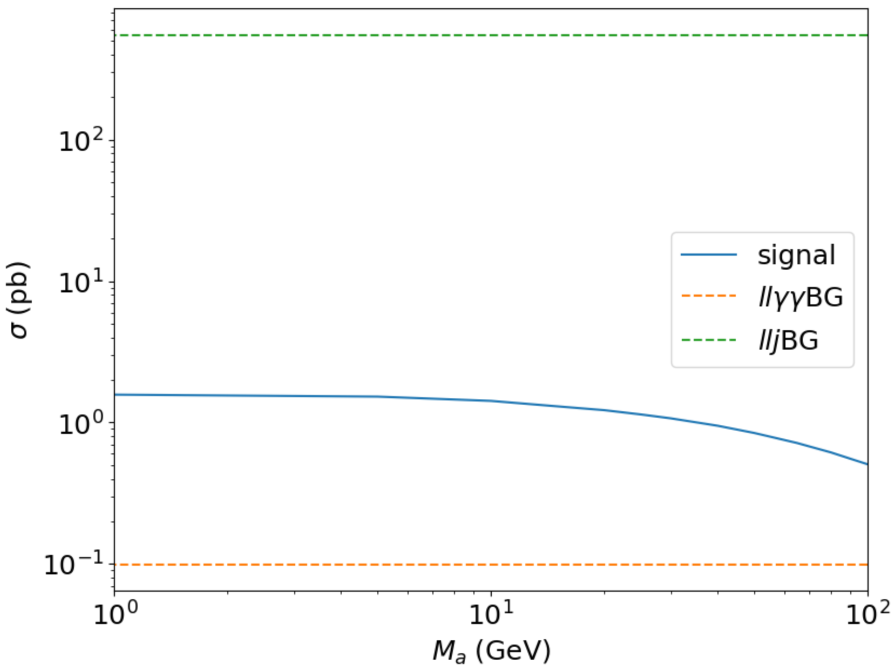


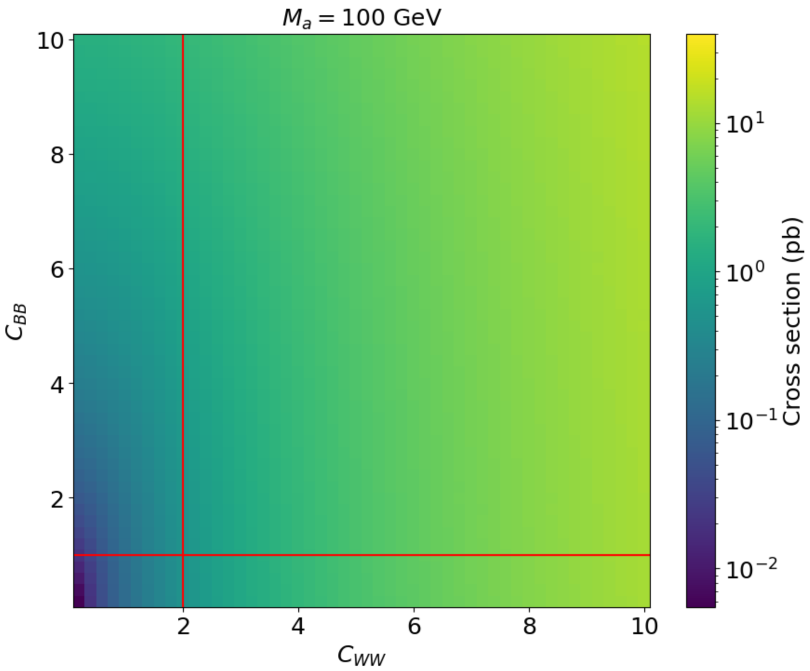
Note:

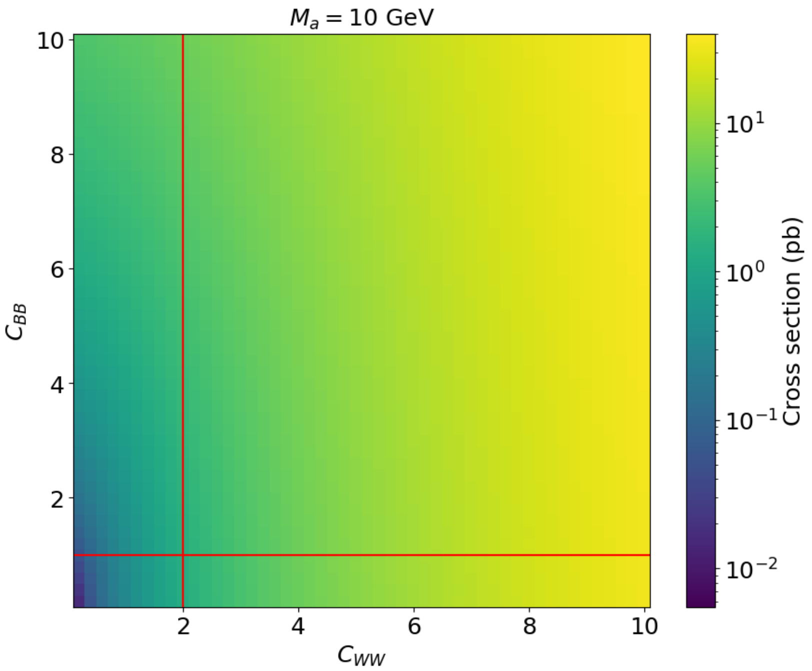
$$g_{aZZ} = \frac{4}{f_a}(C_{BB}{s_w}^2 + C_{WW}{c_w}^2)$$

$$g_{aZ\gamma} = \frac{8}{f_a}(C_{WW} - C_{BB})c_w s_w$$

Signal Events (Z channel)







Background Events (Z channel)

- Signal: $pp \to Za(Z \to l^+l^-)(a \to \gamma\gamma)$
- A cutoff $M_a = 25\ GeV$ is applied.
- $25\ GeV \le M_a \le 100\ GeV$
  1. $pp \to l^+l^-\gamma\gamma\ (ll\gamma\gamma BG)$
  2. $pp \to l^+l^-j\gamma\ (llj\gamma BG)$ with $f_{j\to\gamma} \approx 5 \times 10^{-4}$

  (Credit: ATL-PHYS-PUB-2017-001)
- $1\ GeV < M_a \le 25\ GeV$
  1. $pp \to l^+l^-\gamma\gamma\ (ll\gamma\gamma BG)$
  2. $pp \to l^+l^-j\ (lljBG)$

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Selection Method (Z channel)

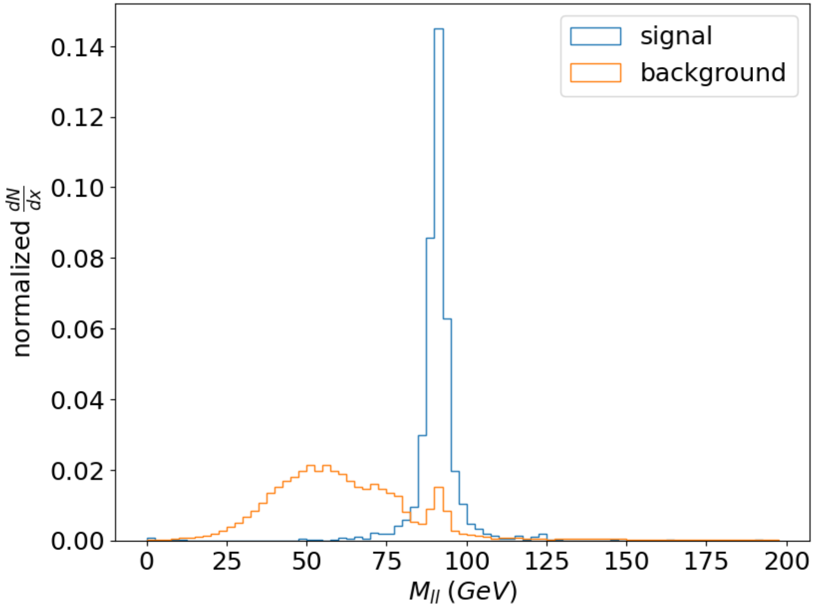
- Large mass region($M_a > 25\ GeV$)
  1. $N_\gamma = 2$
  2. $N_l = 2$
  3. $80\ GeV < M_{ll} < 100\ GeV$
  4. $p_{T_{\gamma\gamma}} > 80\ GeV$
  5. $0.9M_a < M_{\gamma\gamma} < 1.1M_a$

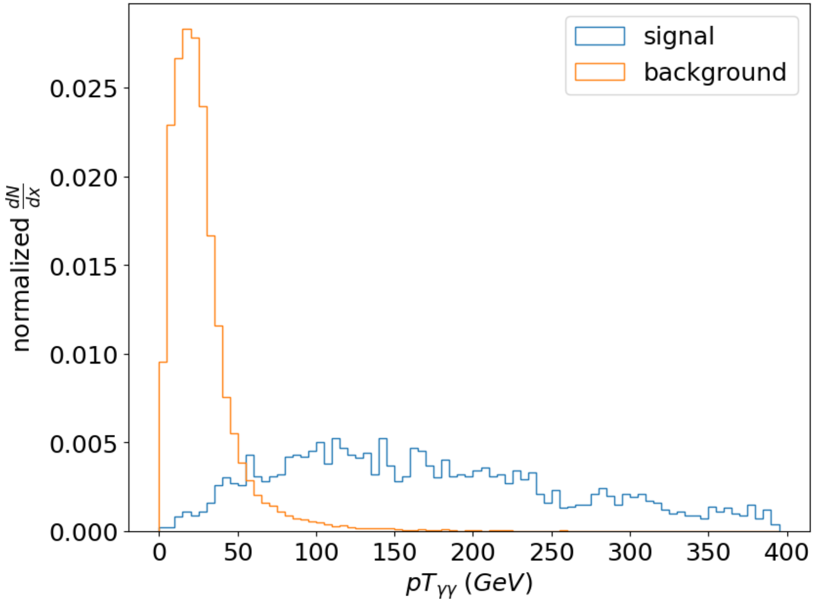
- Small mass region($M_a \leq 25\ GeV$)
  1. $N_j \geq 1$
  2. $\min\left(\frac{E_{had}}{E_{EM}}\right) < 0.02$
  3. $N_l = 2$
  4. $80\ GeV < M_{ll} < 100\ GeV$
  5. $\frac{\tau_2}{\tau_1} < 0.05$
  6. M_{jet} mass window

Selection Method

- Large mass region
  1. $N_\gamma = 2$
  2. $N_l = 2$
  3. $80\ GeV < M_{ll} < 100\ GeV$
  4. $p_{T_{\gamma\gamma}} > 80\ GeV$
  5. $0.9M_a < M_{\gamma\gamma} < 1.1M_a$

- For W channel: $M_{ll} \rightarrow M_T$





Selection Method (Z channel)

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- Large mass region
  1. $N_{\gamma} = 2$
  2. $N_{l} = 2$
  3. $80\ GeV < M_{ll} < 100\ GeV$
  4. $p_{T_{\gamma\gamma}} > 80\ GeV$
  5. $0.9M_a < M_{\gamma\gamma} < 1.1M_a$

$$M_a = 100\ GeV, \mathcal{L} = 300 fb^{-1}$$

Selection	**Signal**	$ll\gamma\gamma$**BG**	$ll\gamma j$**BG**
Before cuts	151948	29728	1048
$N(\gamma) = 2$	69243	12387	61.30
$N(l) = 2$	32152	5488	2.83
80 GeV < $\mathrm{M_{ll}}$ < 100 GeV	29584	739	0.60
$pT_{\gamma\gamma} >$ GeV	24965	90	0.05
90 GeV < $\mathrm{M}_{\gamma\gamma}$ < 110 GeV	24707	13	0.02

$$s, b = \sigma_{s,b} \times \frac{N_{seleciton}}{N_{sim}} \times \mathcal{L}$$

Selection Method (Z channel)

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \times \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$$

For ideal ALP jet, $\frac{\tau_2}{\tau_1} = 0$.

M_a (GeV)	M_{jet} **selection** (GeV)
25	$22.5 < M_{jet} < 30$
20	$18 < M_{jet} < 24$
10	$9 < M_{jet} < 12$
5	$4.5 < M_{jet} < 6$
1	$0.5 < M_{jet} < 2$

- Small mass region
  1. $N_j \geq 1$
  2. $\min\left(\frac{E_{had}}{E_{EM}}\right) < 0.02$
  3. $N_l = 2$
  4. $80\ GeV < M_{ll} < 100\ GeV$
  5. $\frac{\tau_2}{\tau_1} < 0.05$
  6. M_{jet} mass window

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Selection Method (Z channel)

$M_a = 10\ GeV, \mathcal{L} = 300\ fb^{-1}$

Selection	Signal	$ll\gamma\gamma$ BG	llj BG
Before cuts	426413	29728	164921970
$N(jet) \geq 1$	356610	17327	139649327
$min(\frac{E_{had}}{E_{EM}}) < 0.02$	267532	8150	26141121
$N(l) = 2$	88523	1169	649627
80 GeV $<$ M_{ll} $<$ 100 GeV	81957	181	460297
$\frac{\tau_2}{\tau_1} < 0.05$	62811	46	36613
9 GeV $<$ M_{jet} $<$ 12 GeV	48995	0	0

$$s, b = \sigma_{s,b} \times \frac{N_{seleciton}}{N_{sim}} \times \mathcal{L}$$

- Small mass region
  1. $N_j \geq 1$
  2. $\min\left(\frac{E_{had}}{E_{EM}}\right) < 0.02$
  3. $N_l = 2$
  4. $80\ GeV < M_{ll} < 100\ GeV$
  5. $\frac{\tau_2}{\tau_1} < 0.05$
  6. M_{jet} mass window

Numerical Result

Numerical Result (Z channel)

M_a (GeV)	**Signal**		$ll\gamma\gamma$**BG**+$ll\gamma j$**BG**		llj**BG**	
	before	after	before	after	before	after
100	151947	24707		12.80		
80	184160	25211		12.78		
65	214813	23522		7.13		
50	253073	23207	30775	4.16	-	
40	284456	19286		3.87		
30	321176	12205		2.97		
25	342005	25206		0		0
20	366568	34311		0		0
10	426413	48995	29728	0	164950770	0
5	457138	48914		0.59		165
1	472141	46175		29.43		18474

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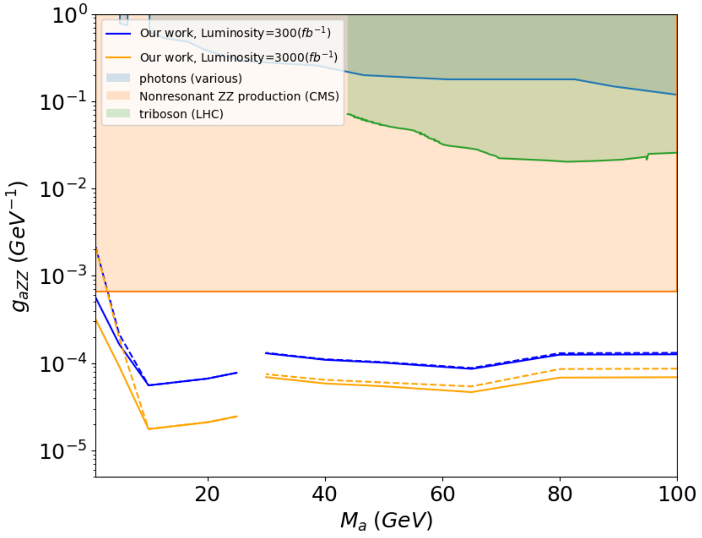
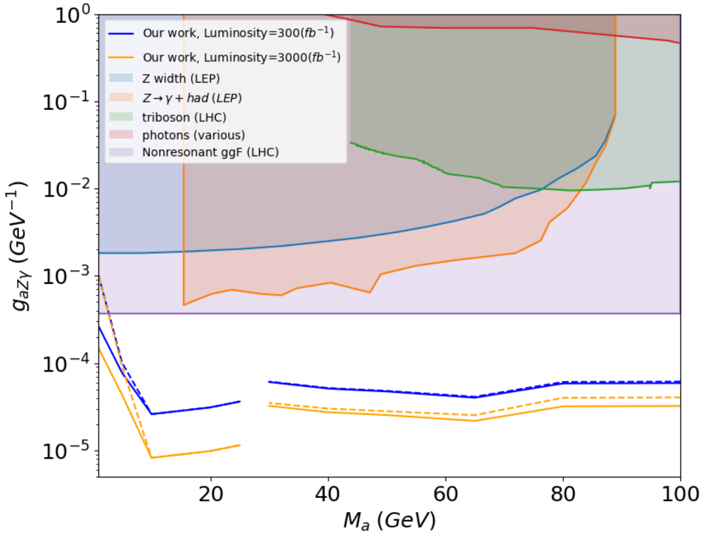
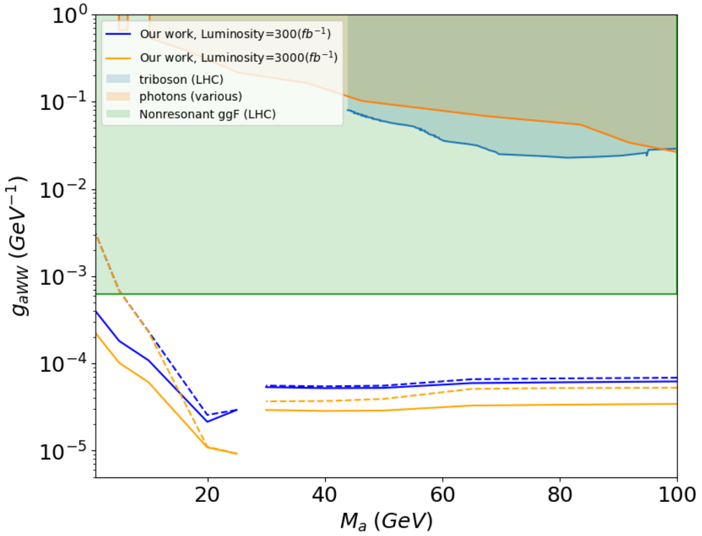
Numerical Result (W channel)

M_a (GeV)	**Signal**		$l\nu_l\gamma\gamma$**BG** $+l\nu_l\gamma j$**BG**		$l\nu_l j$**BG**	
	before	after	before	after	before	after
100	1375200	230208		48.01		
80	1674900	244870		52.87		
65	1992000	261151		57.09		
50	2357400	245170	33579	36.57		
40	2690700	220906		26.43		
30	3066000	193771		21.05		
25	3267000	224443		0		0
20	3555000	290799		0.57		0
10	4218000	461449	28311	1.98	1766100000	1766
5	4575000	522007		6.79		17661
1	4797000	469147		110		326729

Numerical Result



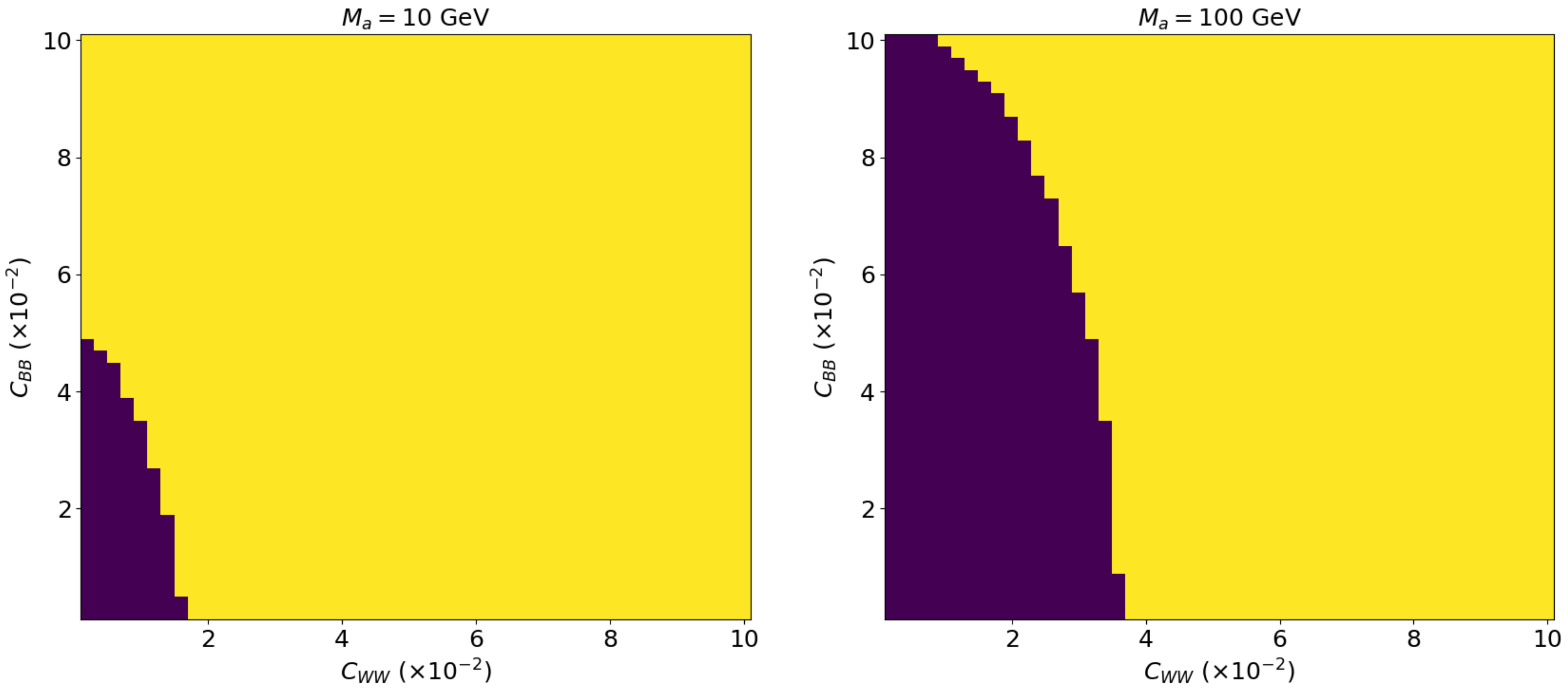




$$Z = \sqrt{2\left[(s+b)\ln\left(\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right) - \frac{b^2}{\sigma_b^2}\ln\left(1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right)\right]}$$

Remark: for $M_a < 10$ GeV, referring these papers for improvement:
Photon-jet events as a probe of axionlike particles at the LHC, 2102.01532
Detecting an axion-like particle with machine learning at the LHC, 2106.07018

Numerical Result



Summary

Summary

- We investigate the behavior of ALP-gauge boson coupling $g_{aZZ}, g_{aZ\gamma}$ and g_{aWW} at $\mathcal{L} = 300\ fb^{-1}, 3000 fb^{-1}$ and $\sqrt{s} = 14\ TeV$.
- We gives a procedure to move out most of the background and enhance the signal efficiency.
- We show the sensitivity of $g_{aZZ}, g_{aZ\gamma}$ and g_{aWW} can be improved around one order of magnitude compared to the current limit in the mass range $1\ GeV \ \leq M_a \leq 100\ GeV$.