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CTEHEP-LNNU

Searching for axion-like particles at future e^+e^- and e^-p colliders

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27th Mini-workshop on the frontier of LHC

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Based on Phys.Lett.B 848 (2024) 138368 with **C.-X. Yue** and Y.-Q. Wang
Phys.Rev.D 107 (2023) 11, 115025 with **C.-X. Yue**, X.-J Cheng and Y.-Q. Wang
J.Phys.G 49 (2022) 11, 115002 with **C.-X. Yue**, Y.-C. Guo, X.-J Cheng and X.-Y. Li

Outline

1 Introduction

2 Searching for axion-like particles at the CEPC via the triphoton channel

3 Sensitivity of the future $e^{-}p$ collider to the coupling of axion-like particles with $W^{\pm}$ bosons

4 Detecting the coupling of axion-like particles with fermions at the ILC

5 Conclusions

1.1 Properties of axion-like particles (ALPs)

- generalizations of QCD axions
- CP-odd neutral pseudoscalars

singlets

- the masses
  couplings to the SM particles
  ] independent parameters

1.2 Effective interactions of ALP

The effective interactions of ALP with the SM particles:

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial^{\mu} a)(\partial_{\mu} a) - \frac{1}{2} m_a^2 a^2 + \frac{\partial^{\mu} a}{f_a} \sum_{\substack{\psi = Q_L, Q_R, \\ L_L, L_R}} \bar{\psi}\gamma_{\mu} X_{\psi} \psi - C_{\tilde{B}} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} - C_{\tilde{W}} \frac{a}{f_a} W^{i}_{\mu\nu} \tilde{W}^{i\mu\nu}$$

m_a : the mass of ALP

f_a : the characteristic scale

$W^{i}_{\mu\nu}$ *and* $B_{\mu\nu}$: the field strength tensors of $SU(2)_L$ *and* $U(1)_Y$

$C_{\tilde{W}}$ *and* $C_{\tilde{B}}$: the coupling constants

X_{ψ} : Hermitian matrices in flavour space

After electroweak symmetry breaking:

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial^{\mu}a)(\partial_{\mu}a) - \frac{1}{2}m_a^2 a^2 + i g_{a\psi} a \sum_{\psi=Q,L} m_{\psi}^{diag} \bar{\psi}\gamma_5\psi$$
$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4} g_{aZZ} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{1}{4} g_{a\gamma Z} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{1}{4} g_{aWW} a W_{\mu\nu}\tilde{W}^{\mu\nu}$$

m_{ψ}^{diag} : the diagonalizable fermion mass matrix

$F_{\mu\nu}$: the photon field strength tensor

$Z_{\mu\nu}$: the Z boson field strength tensor

$W_{\mu\nu}$: the W boson field strength tensor all the couplings $g_{a\gamma\gamma}$, g_{aZZ}, $g_{aZ\gamma}$, g_{aWW} *and* $g_{a\psi}$ are governed by f_a

where

$$g_{a\gamma\gamma}=\frac{4}{f_a}(c_W^2C_{\tilde{B}}+s_W^2C_{\tilde{W}}),\quad g_{aZZ}=\frac{4}{f_a}(s_W^2C_{\tilde{B}}+c_W^2C_{\tilde{W}}),$$

$$g_{a\gamma Z}=\frac{8}{f_a}s_Wc_W(C_{\tilde{W}}-C_{\tilde{B}}),\quad g_{aWW}=\frac{4}{f_a}C_{\tilde{W}}$$

s_W *and* c_W : the sine and cosine of the weak mixing angle

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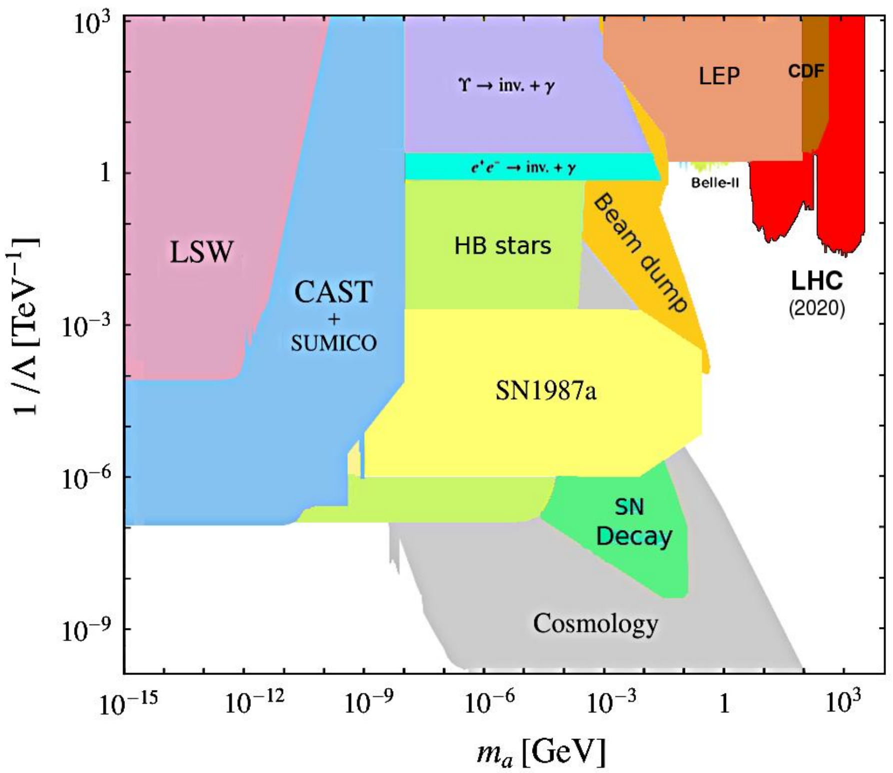
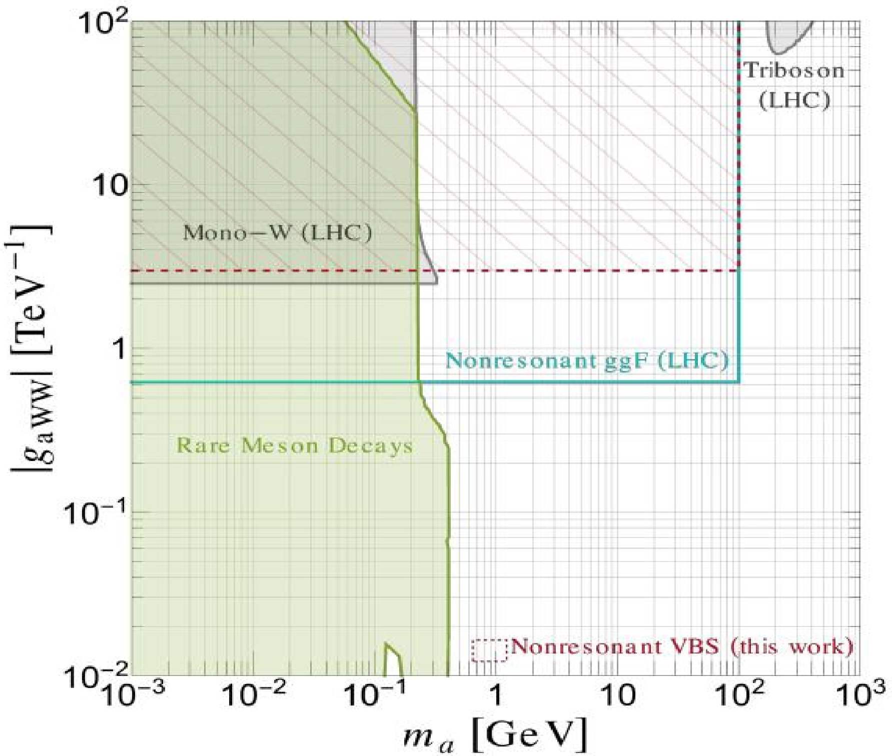
1.3 The constraints on the effective couplings of ALP to the SM bosons or fermions

D. d'Enterria, in *Workshop on Feebly Interacting Particles* (2021), 2102.08971



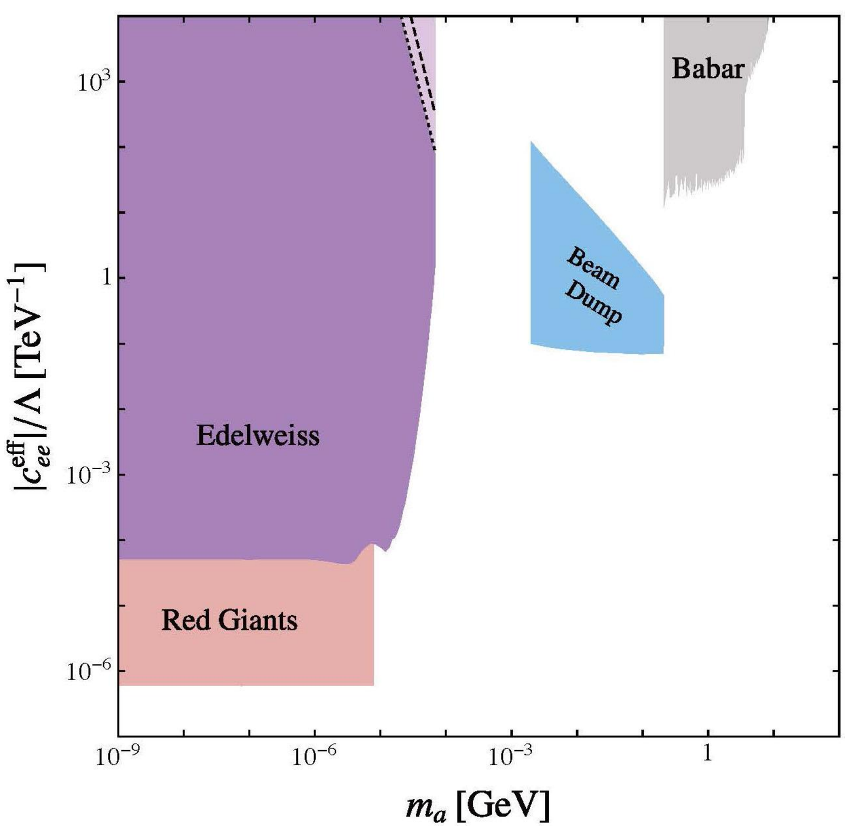
J. Bonilla, I. Brivio, J. Machado-Rodríguez, and J. F. de Trocóniz, JHEP **06**, 113 (2022), 2202.03450



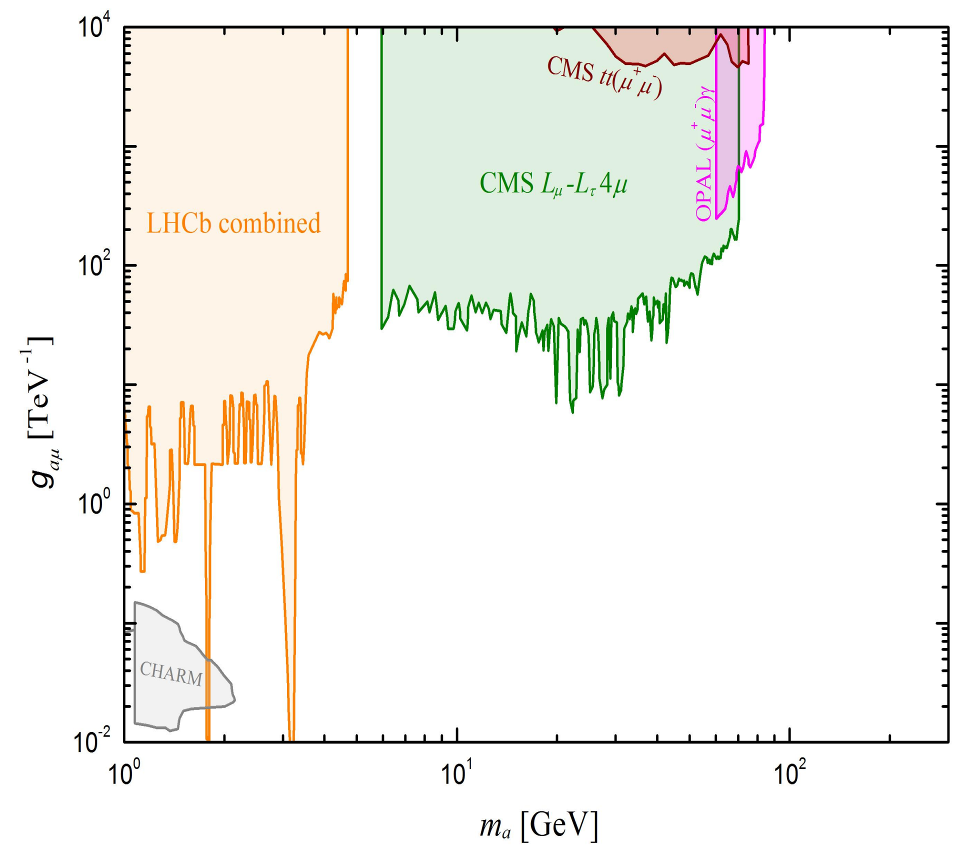
Existing constraints on the ALP–photon coupling (left) and ALP–$W^{\pm}$ coupling (right)

1.3 The constraints on the effective couplings of ALP to the SM bosons or fermions

M. Bauer, M. Neubert, and A. Thamm, JHEP **12**, 044 (2017), 1708.00443



J. Liu, X. Ma, L.-T. Wang, and X.-P. Wang, Phys. Rev. D **107**, 095016 (2023), 2210.09335



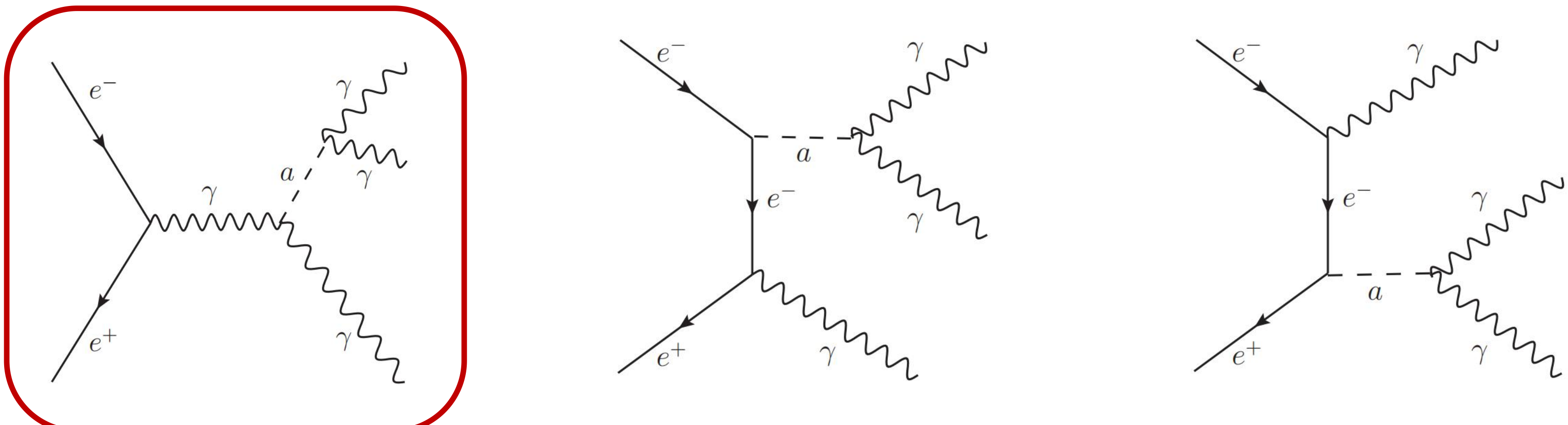
Existing constraints on the ALP–electron coupling (left) and ALP–muon coupling (right)

J.Phys.G 49 (2022) 11, 115002

Han Wang, Chong-Xing Yue*, Yu-Chen Guo, Xue-Jia Cheng and Xin-Yang Li

- $C_{\tilde{W}} = C_{\tilde{B}} \longrightarrow = g_{a\gamma\gamma} = g_{aZZ} = g_{aWW}$ *and* $g_{a\gamma Z} = 0$

- The Feynman diagrams for the process of $e^+e^- \to a\gamma \to 3\gamma$

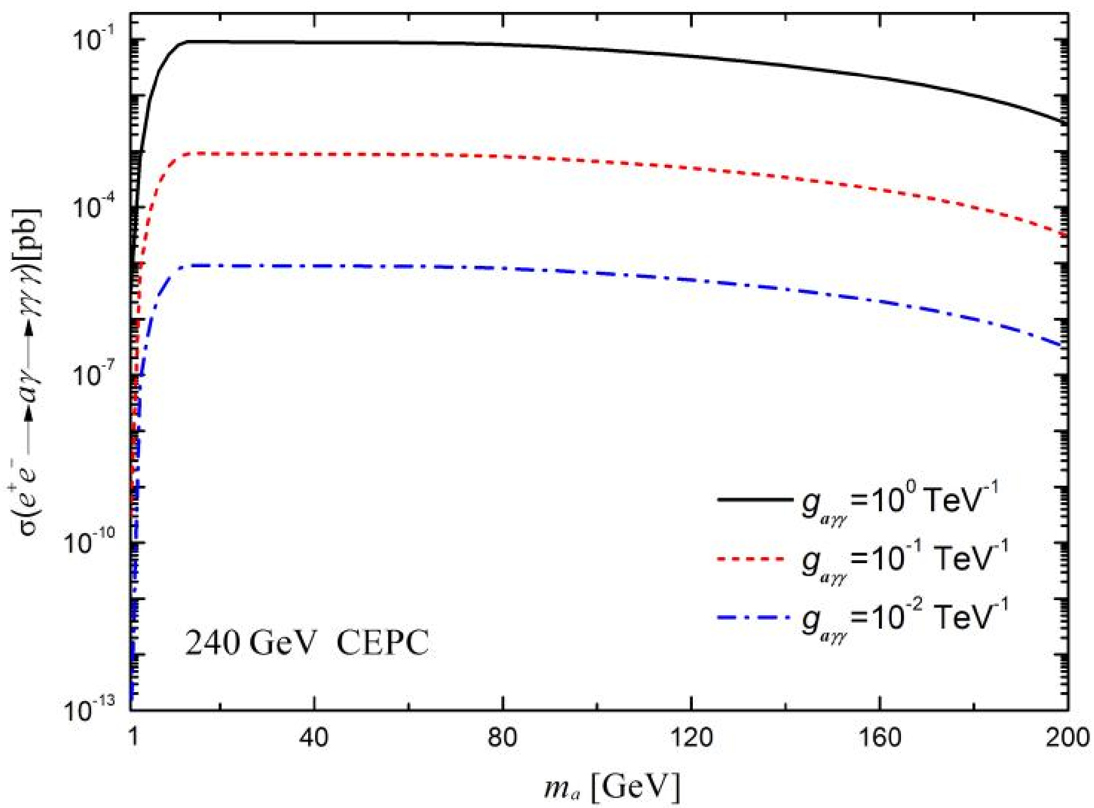


(a) (b) (c)

(a) → **dominant**

- CEPC $E_{CM} = 240\ \text{GeV}$ $\mathcal{L} = 5.6\ \text{ab}^{-1}$ $1\,\text{GeV} < m_a \leq 200\,\text{GeV}$

- The cross section of the process $e^+e^- \to a\gamma \to 3\gamma$ as a function of the ALP mass m_a



- Basic cuts:

$$p_T^{\gamma} > 10\ \text{GeV}$$

$$\left|\eta_{\gamma}\right| < 2.5$$

$$\Delta R_{\gamma\gamma} > 0.2 \qquad (\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$$

Tools added:

MLAnalysis https://github.com/NBAlexis/MLAnalysis

- The angular separation of the two photons from ALP decay strongly depends on the ALP mass

- $m_a \leq 20\,\mathrm{GeV}$ → $N_\gamma \geq 1$

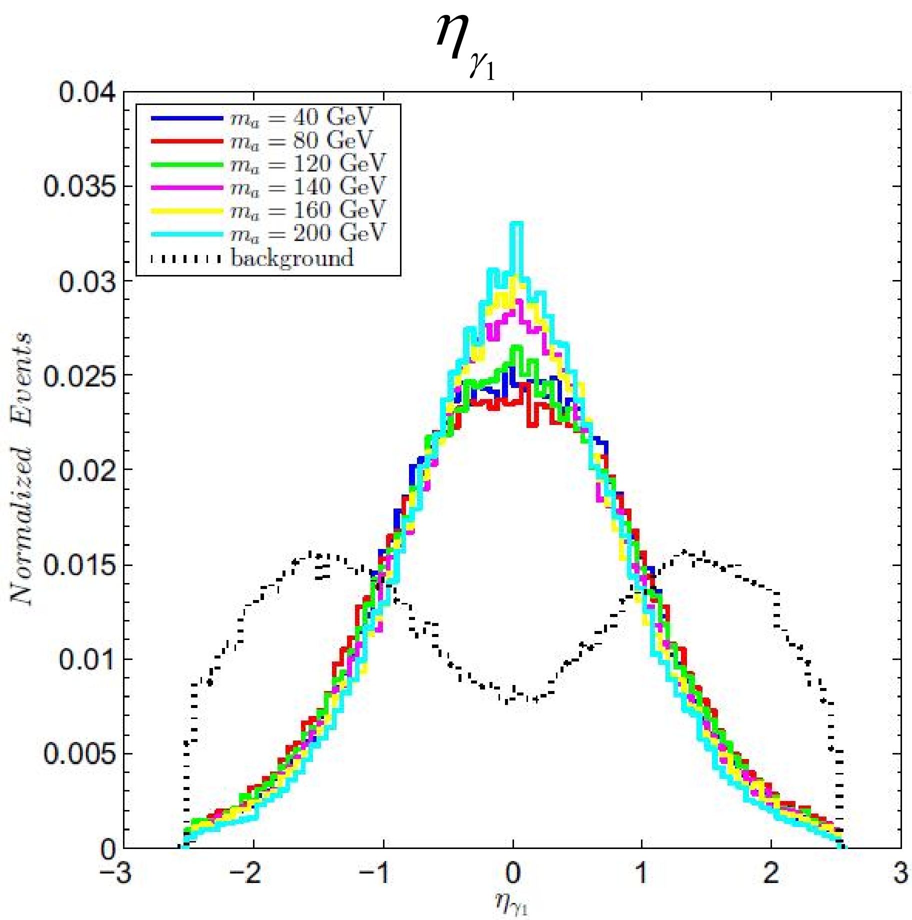
  the invariant mass of all final state photons m_γ

  the transverse momentum of the hardest photon in the final states $p_T^{\gamma_1}$

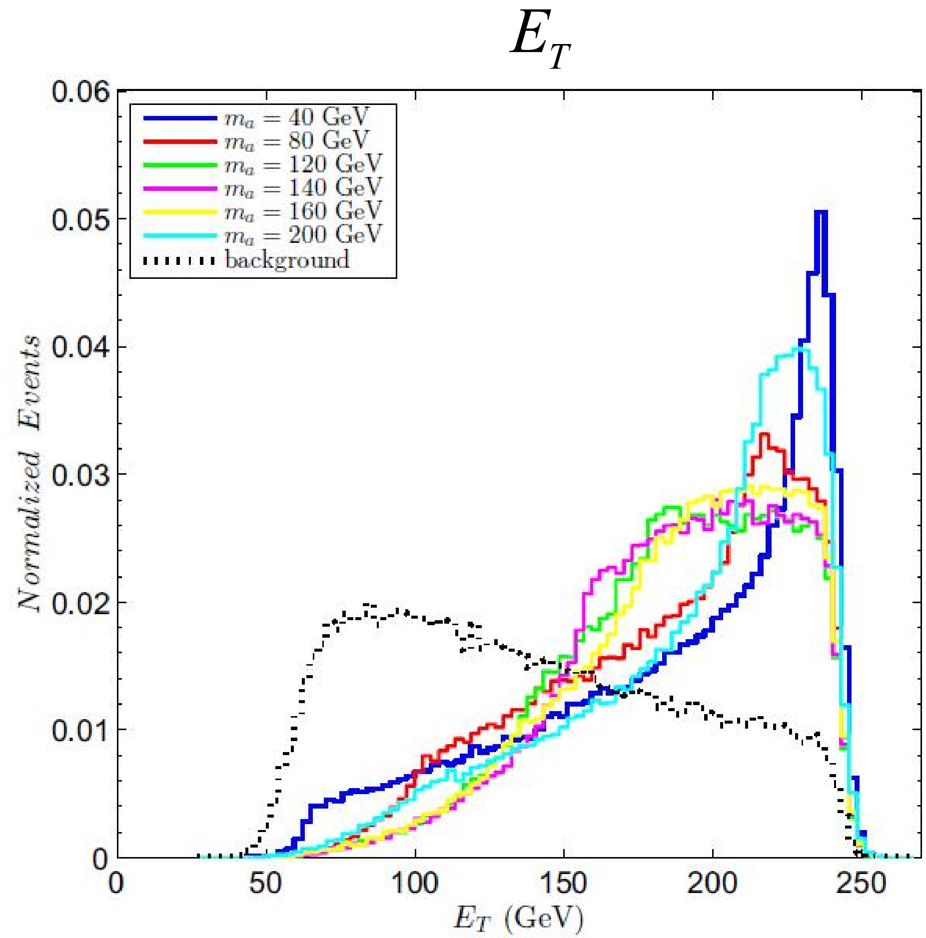
  } observables

- $m_a > 20\,\mathrm{GeV}$ → $N_\gamma \geq 3$

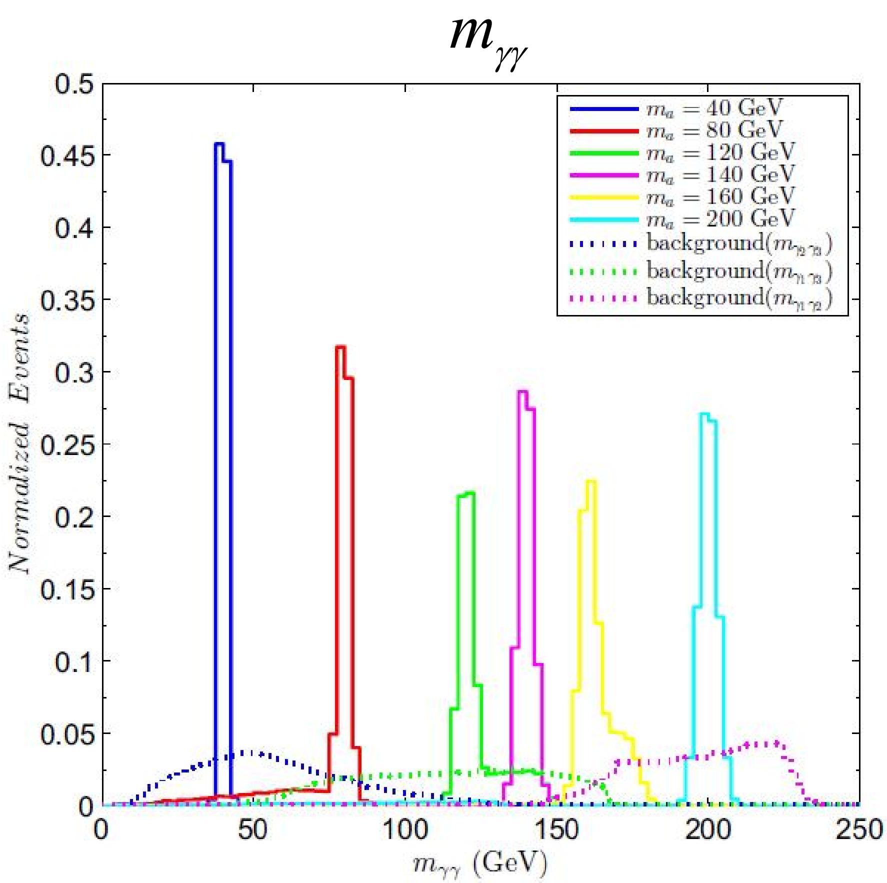
  η_{γ_1} E_T $m_{\gamma\gamma}$ → observables



η_{γ_1}
$m_a = 40$ GeV
$m_a = 80$ GeV
$m_a = 120$ GeV
$m_a = 140$ GeV
$m_a = 160$ GeV
$m_a = 200$ GeV
background
Normalized Events
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−3
−2
−1
0
1
2
3
η_{γ_1}



E_T
$m_a = 40$ GeV
$m_a = 80$ GeV
$m_a = 120$ GeV
$m_a = 140$ GeV
$m_a = 160$ GeV
$m_a = 200$ GeV
background
Normalized Events
0.06
0.05
0.04
0.03
0.02
0.01
0
0
50
100
150
200
250
E_T (GeV)



- The symbols γ_1, γ_2 *and* γ_3 :

  The photons with the largest, intermediate and smallest momentum

- high mass ALP → $\gamma_1\gamma_2$

  low mass ALP → $\gamma_2\gamma_3$

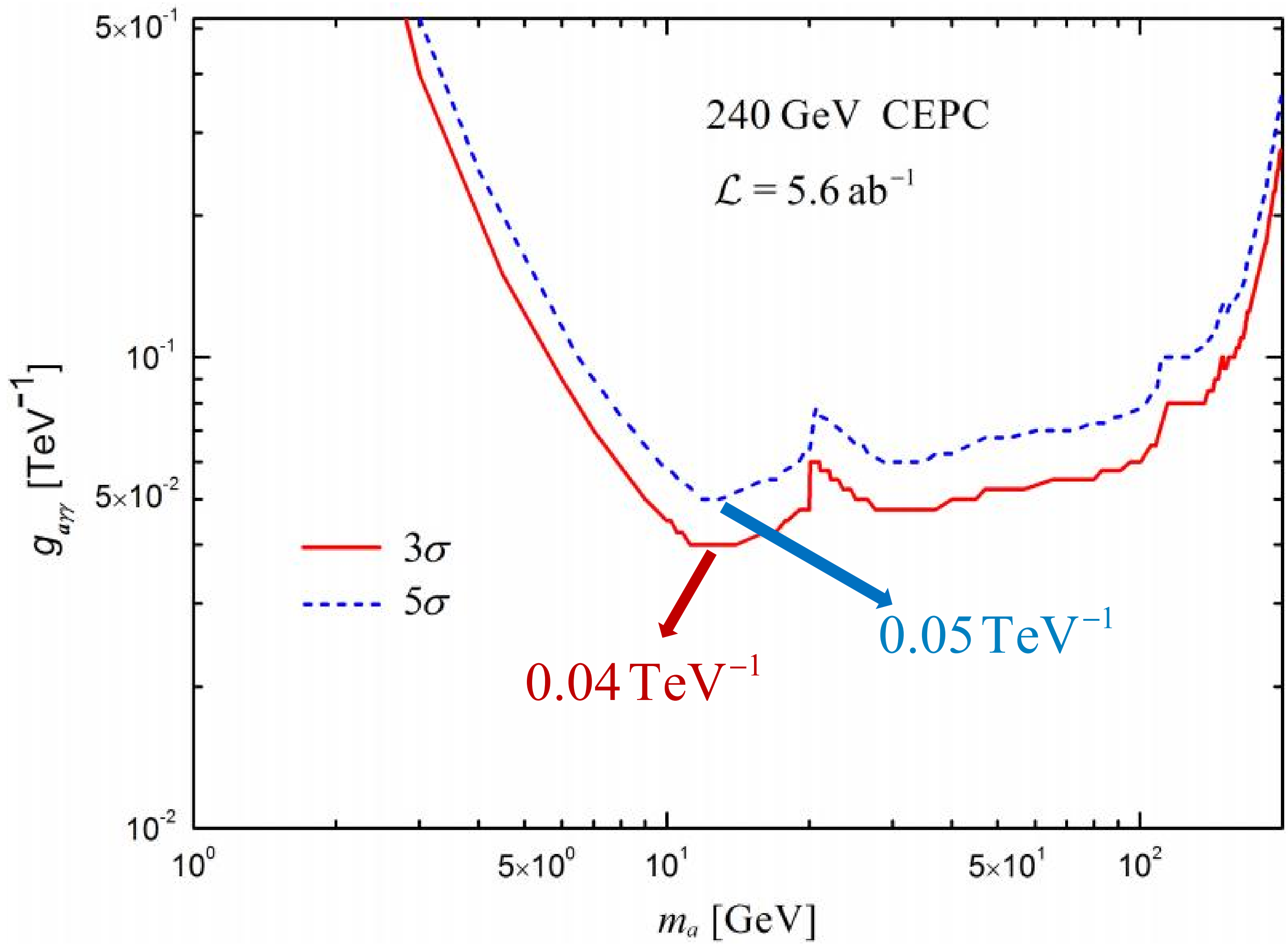
- The improved cuts

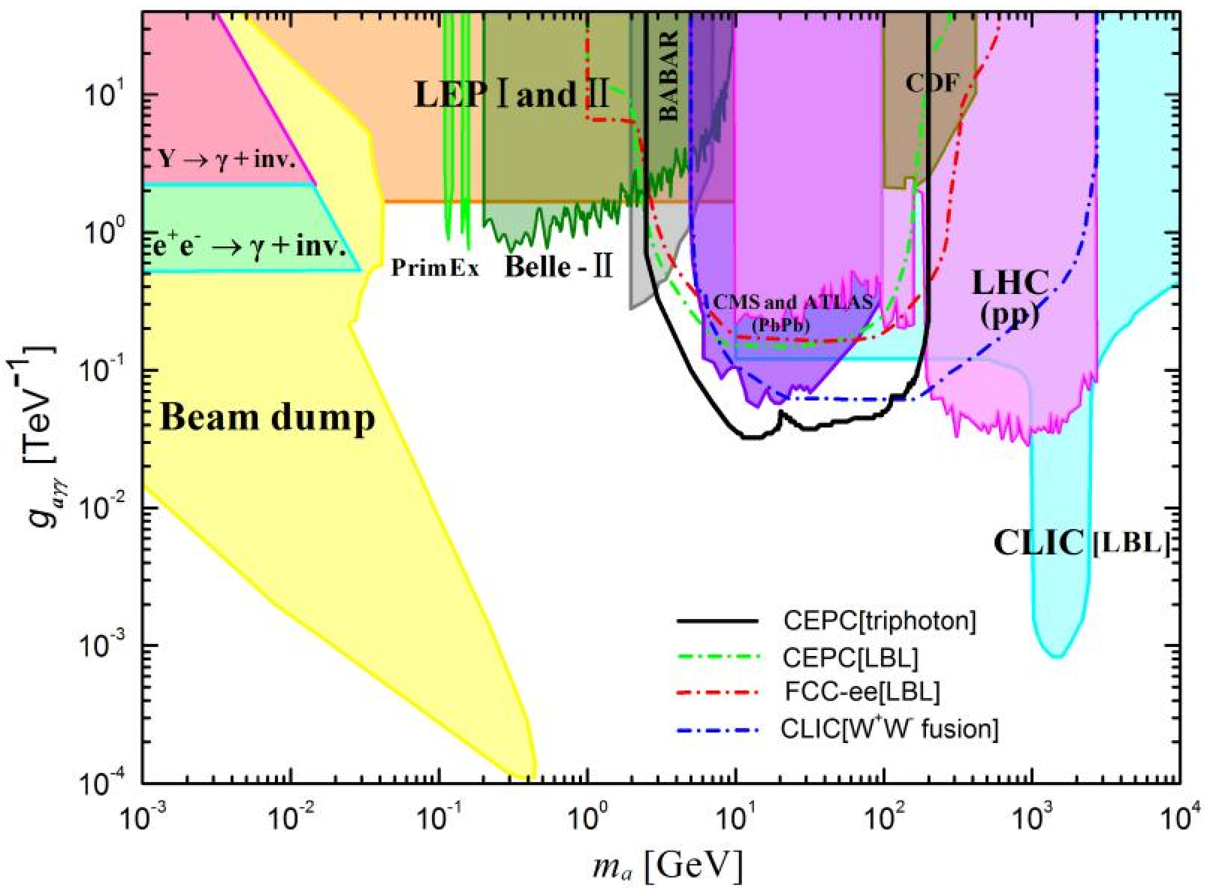
Cut \ mass	$1\ \text{GeV} < m_a \leq 20\ \text{GeV}$	$20\ \text{GeV} < m_a \leq 200\ \text{GeV}$
Cut1	$N_\gamma \geq 1$	$N_\gamma \geq 3$
Cut2	$m_\gamma \leq 20\ \text{GeV}$	$\lvert\eta_{\gamma_1}\rvert < 1.7$
Cut3	$p_T^{\gamma_1} \geq 20\ \text{GeV}$	$E_T \geq 100\ \text{GeV}$
Cut4	–	$\lvert m_{\gamma\gamma} - m_a\rvert \leq 5\ \text{GeV}$

m_a [GeV]	cross sections for signal(background)[pb]					SS
	Basic Cuts	Cut1	Cut2	Cut3	Cut4	
10	6.5893×10^{-4}(0.2851)	6.5303×10^{-4}(0.2850)	5.8278×10^{-4}(0.0087)	5.8259×10^{-4}(0.0086)	–	14.38
20	9.0768×10^{-4}(0.2851)	9.0260×10^{-4}(0.2850)	4.9382×10^{-4}(0.0087)	4.9369×10^{-4}(0.0086)	–	12.24
40	8.9170×10^{-4}(0.2851)	8.1998×10^{-4}(0.2679)	7.7072×10^{-4}(0.1842)	7.5997×10^{-4}(0.1739)	7.5569×10^{-4}(0.0202)	12.35
80	8.0760×10^{-4}(0.2851)	7.3533×10^{-4}(0.2679)	6.8321×10^{-4}(0.1842)	6.7924×10^{-4}(0.1739)	5.4713×10^{-4}(0.0178)	9.56
120	5.0300×10^{-4}(0.2851)	4.5322×10^{-4}(0.2679)	4.2267×10^{-4}(0.1842)	4.2141×10^{-4}(0.1739)	2.8405×10^{-4}(0.0189)	4.85
140	3.4438×10^{-4}(0.2851)	3.0861×10^{-4}(0.2679)	2.8993×10^{-4}(0.1842)	2.8918×10^{-4}(0.1739)	2.5867×10^{-4}(0.0204)	4.26
160	2.0613×10^{-4}(0.2851)	1.8364×10^{-4}(0.2679)	1.7283×10^{-4}(0.1842)	1.7234×10^{-4}(0.1739)	1.2056×10^{-4}(0.0103)	2.80
200	3.0873×10^{-5}(0.2851)	2.7060×10^{-5}(0.2679)	2.5737×10^{-5}(0.1842)	2.5585×10^{-5}(0.1739)	2.3273×10^{-5}(0.0251)	0.35

- $g_{a\gamma\gamma} = 10^{-4}\ \mathrm{GeV}^{-1}$

- The 3σ and 5σ curves for the process $e^+e^- \to a\gamma \to 3\gamma$ in the $(m_a, g_{a\gamma\gamma})$ plane





- The promising sensitivities as $g_{a\gamma\gamma} \in [0.0325, 0.37]\,\mathrm{TeV}^{-1}$ with $m_a \in [2.9, 190]$ GeV at 2σ level

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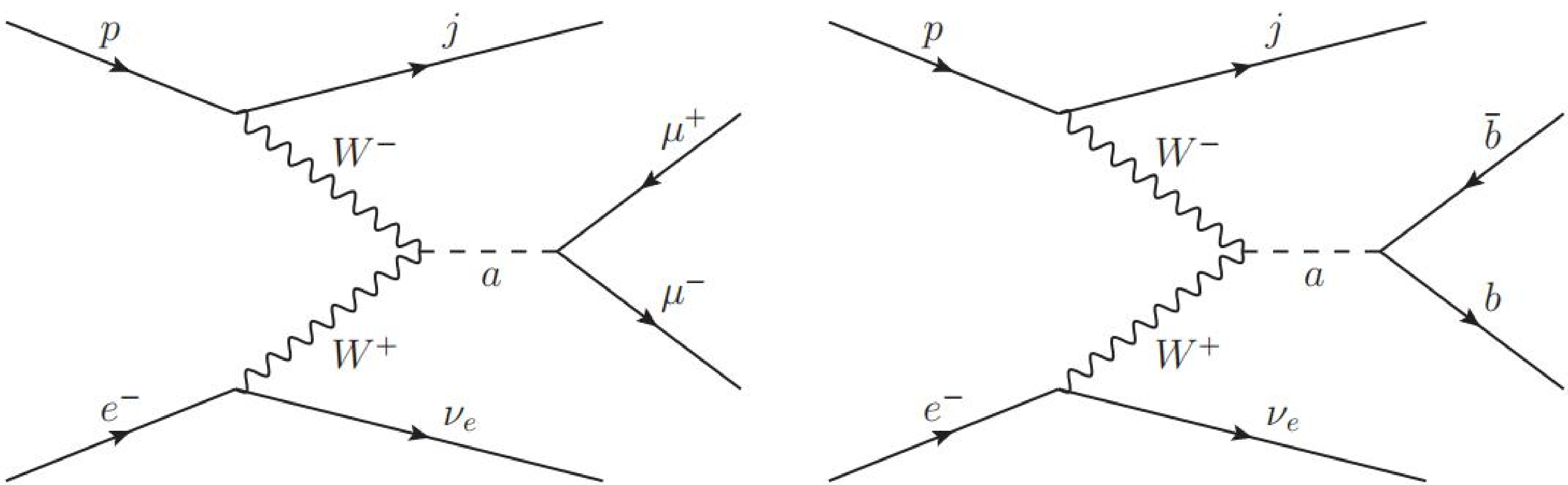
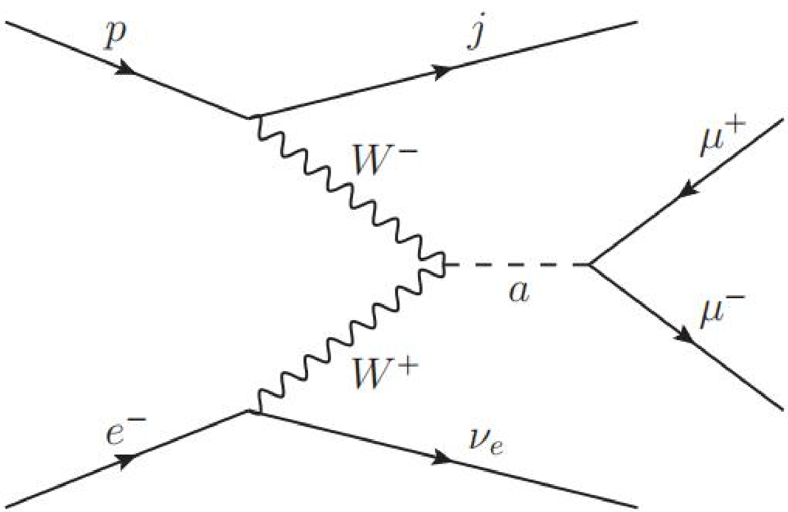
Xue-Jia Cheng and Yue-Qi Wang



$$e^- p \to v_e ja(a \to \mu^+ \mu^-)$$

$$e^- p \to v_e ja(a \to b\bar{b})$$

Searching for ALP via $e^- p \to \nu_e j a(a \to \mu^+\mu^-)$



- LHeC

  $E_{CM} = 1.3\ \text{TeV}$

  $\mathcal{L} = 1\ \text{ab}^{-1}$

- $5\ \text{GeV} \le m_a \le 1000\ \text{GeV}$

- Basic cuts:

  $P_T^l > 10\ \text{GeV}$

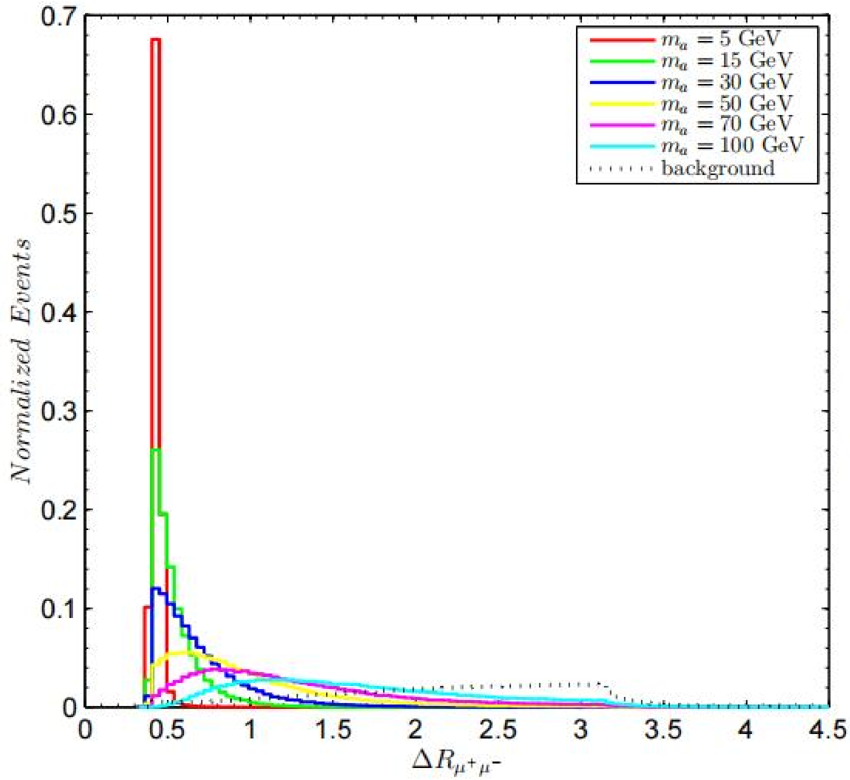
  $P_T^j > 20\ \text{GeV}$

  $|\eta_l| < 2.5 \quad |\eta_j| < 5$

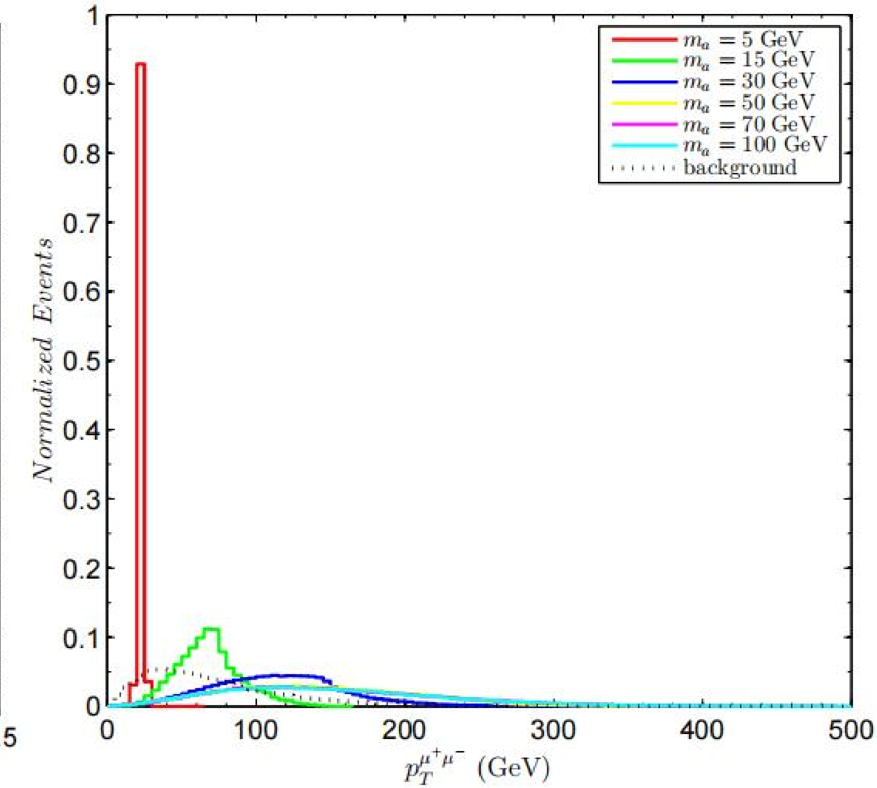
$\Delta R_{ll} > 0.4 \quad \Delta R_{jj} > 0.4 \quad \Delta R_{lj} > 0.4$

- $5\,\mathrm{GeV} \le m_a \le 100\,\mathrm{GeV}$

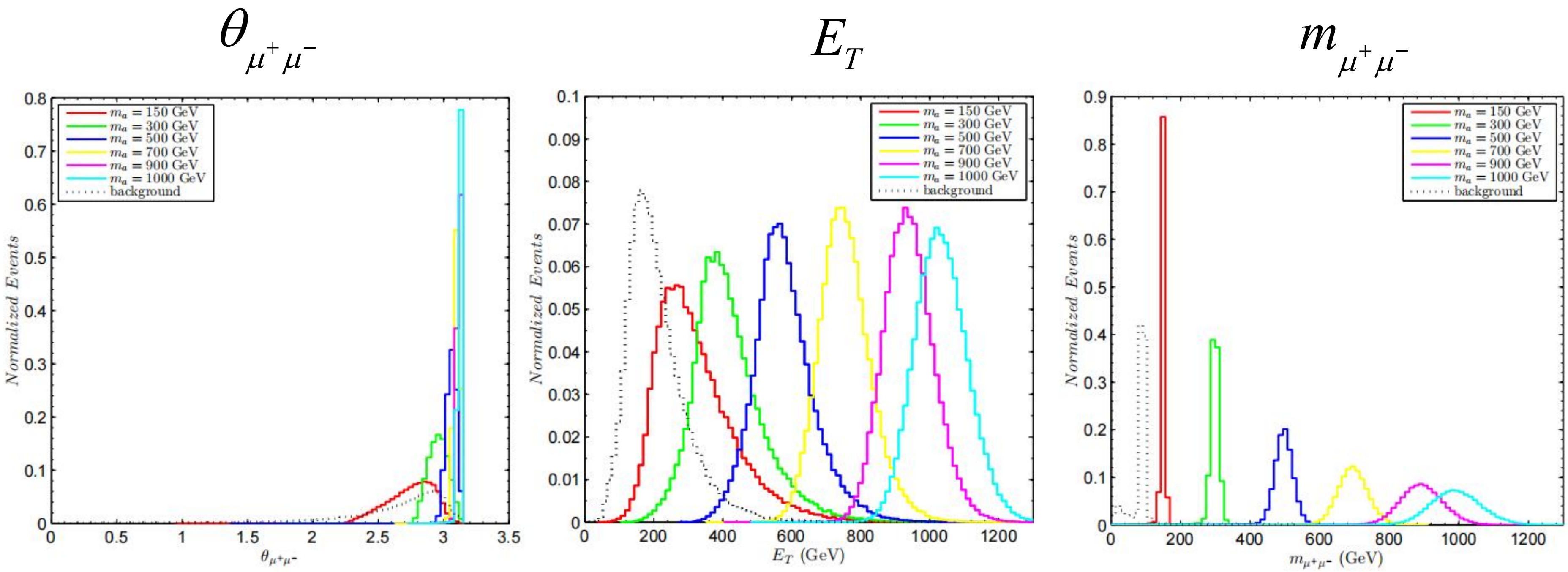
$\Delta R_{\mu^+\mu^-}$



$P_T^{\mu^+\mu^-}$



- $100\,\mathrm{GeV} < m_a \leq 1000\,\mathrm{GeV}$



- The improved cuts

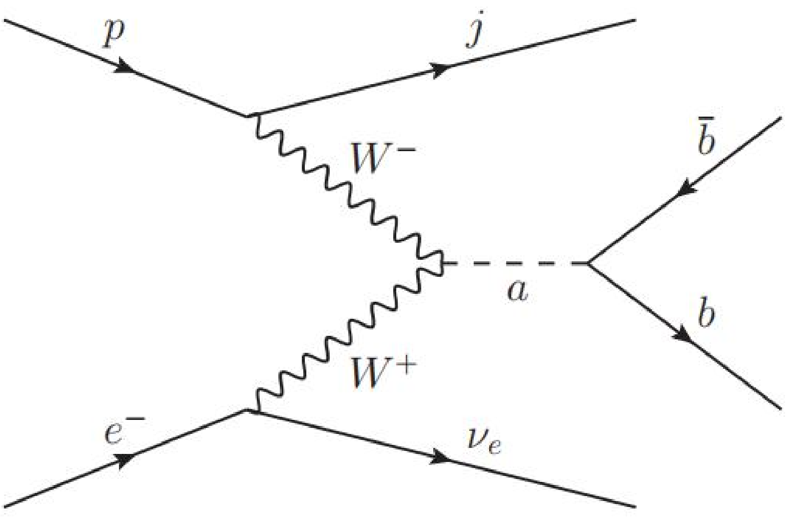
Cuts	Mass	
	$5\ \text{GeV} \leq m_a \leq 100\ \text{GeV}$	$100\ \text{GeV} < m_a \leq 1000\ \text{GeV}$
Cut 1	$N_{\mu^+} \geq 1, N_{\mu^-} \geq 1, N_j \geq 1$	$N_{\mu^+} \geq 1, N_{\mu^-} \geq 1, N_j \geq 1$
Cut 2	$\Delta R_{\mu^+\mu^-} < 1.8$	$\theta_{\mu^+\mu^-} > 2.1$
Cut 3	$p_T^{\mu^+\mu^-} > 20\ \text{GeV}$	$E_T > 250\ \text{GeV}$
Cut 4	–	$m_{\mu^+\mu^-} > 100\ \text{GeV}$

Cuts	cross sections for signal (background) [pb]					
	m_a = 5 GeV	m_a = 15 GeV	m_a = 30 GeV	m_a = 50 GeV	m_a = 70 GeV	m_a = 100 GeV
Basic Cuts	1.7442×10^{-6} (0.0142)	5.2885×10^{-4} (0.0142)	2.0437×10^{-3} (0.0142)	2.8861×10^{-3} (0.0142)	2.9864×10^{-3} (0.0142)	2.7399×10^{-3} (0.0142)
Cut 1	1.4435×10^{-6} (0.0128)	4.6473×10^{-4} (0.0128)	1.8361×10^{-3} (0.0128)	2.6165×10^{-3} (0.0128)	2.7072×10^{-3} (0.0128)	2.4812×10^{-3} (0.0128)
Cut 2	1.4435×10^{-6} (3.9212×10^{-3})	4.6463×10^{-4} (3.9212×10^{-3})	1.8156×10^{-3} (3.9212×10^{-3})	2.4350×10^{-3} (3.9212×10^{-3})	2.2205×10^{-3} (3.9212×10^{-3})	1.5666×10^{-3} (3.9212×10^{-3})
Cut 3	1.3934×10^{-6} (3.8963×10^{-3})	4.6375×10^{-4} (3.8963×10^{-3})	1.8155×10^{-3} (3.8963×10^{-3})	2.4349×10^{-3} (3.8963×10^{-3})	2.2205×10^{-3} (3.8963×10^{-3})	1.5666×10^{-3} (3.8963×10^{-3})
SS	0.022	7.015	24.022	30.609	28.396	21.196

Cuts	cross sections for signal (background) [pb]					
	m_a = 150 GeV	m_a = 300 GeV	m_a = 500 GeV	m_a = 700 GeV	m_a = 900 GeV	m_a = 1000 GeV
Basic Cuts	2.1509×10^{-3} (0.0142)	8.8581×10^{-4} (0.0142)	2.0197×10^{-4} (0.0142)	2.7954×10^{-5} (0.0142)	1.5617×10^{-6} (0.0142)	1.9118×10^{-7} (0.0142)
Cut 1	1.9429×10^{-3} (0.0128)	7.9889×10^{-4} (0.0128)	1.8218×10^{-4} (0.0128)	2.4999×10^{-5} (0.0128)	1.3965×10^{-6} (0.0128)	1.7116×10^{-7} (0.0128)
Cut 2	1.9417×10^{-3} (0.0112)	7.9882×10^{-4} (0.0112)	1.8218×10^{-4} (0.0112)	2.4999×10^{-5} (0.0112)	1.3965×10^{-6} (0.0112)	1.7116×10^{-7} (0.0112)
Cut 3	1.3790×10^{-3} (3.2070×10^{-3})	7.7811×10^{-4} (3.2070×10^{-3})	1.8218×10^{-4} (3.2070×10^{-3})	2.4999×10^{-5} (3.2070×10^{-3})	1.3965×10^{-6} (3.2070×10^{-3})	1.7116×10^{-7} (3.2070×10^{-3})
Cut 4	1.3713×10^{-3} (2.2571×10^{-4})	7.7691×10^{-4} (2.2571×10^{-4})	1.8208×10^{-4} (2.2571×10^{-4})	2.4989×10^{-5} (2.2571×10^{-4})	1.3965×10^{-6} (2.2571×10^{-4})	1.7116×10^{-7} (2.2571×10^{-4})
SS	34.309	24.526	8.986	1.581	0.093	0.011

- $g_{aWW} = 1\,\text{TeV}^{-1}$

Searching for ALP via $e^- p \to \nu_e j a (a \to b\bar{b})$



- $E_{CM} = 1.3$ TeV

  $\mathcal{L} = 1\,\mathrm{ab}^{-1}$
- $15\,\mathrm{GeV} \le m_a \le 1000\,\mathrm{GeV}$
- Basic cuts:

  $P_T^l > 10$ GeV

  $P_T^j > 20$ GeV

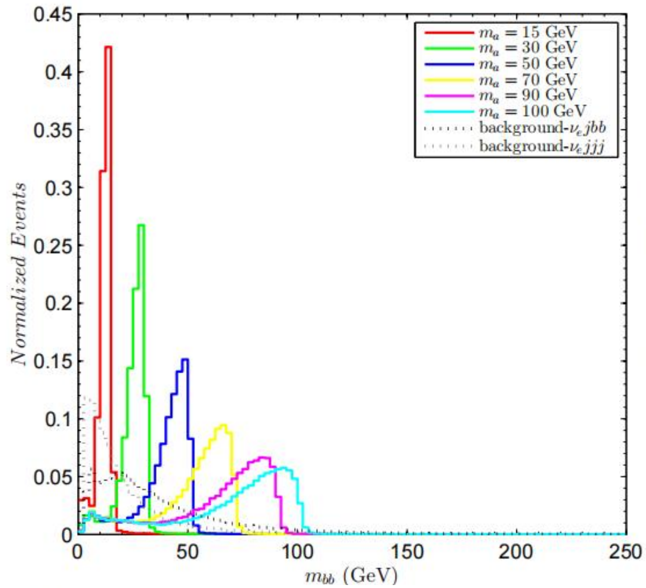
  $|\eta_l| < 2.5 \quad |\eta_j| < 5$

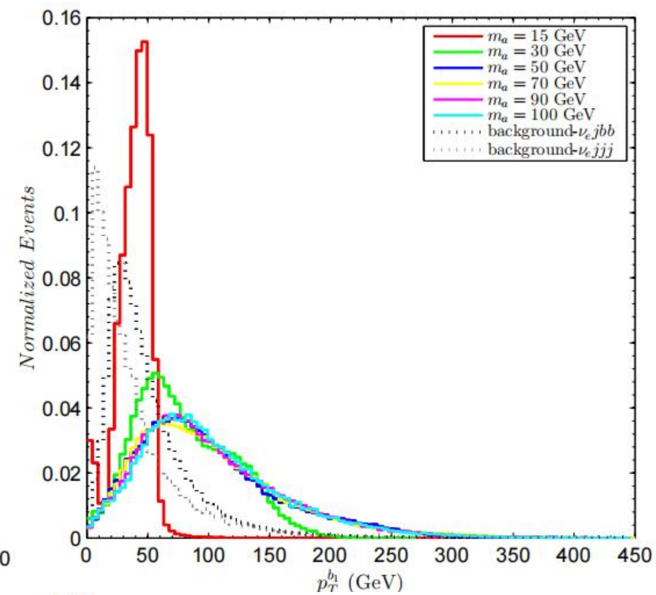
  $\Delta R_{ll} > 0.4 \quad \Delta R_{jj} > 0.4 \quad \Delta R_{lj} > 0.4$

Sensitivity of the future e^-p collider to the coupling of axion-like particles with $W^\pm$ bosons

- $15\,\text{GeV} \le m_a \le 100\,\text{GeV}$

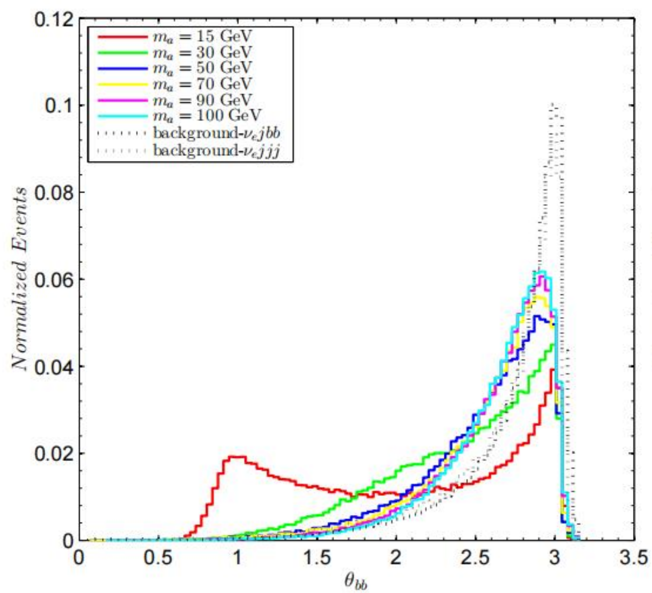
m_{bb}

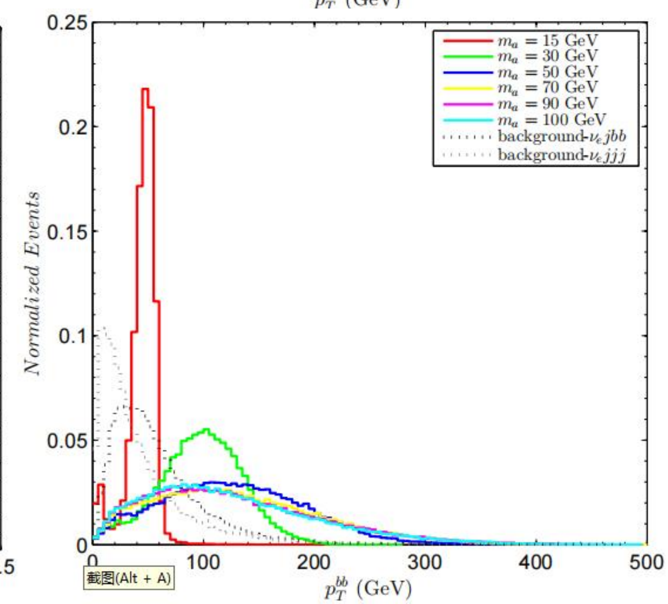




$P_T^{b_1}$

θ_{bb}

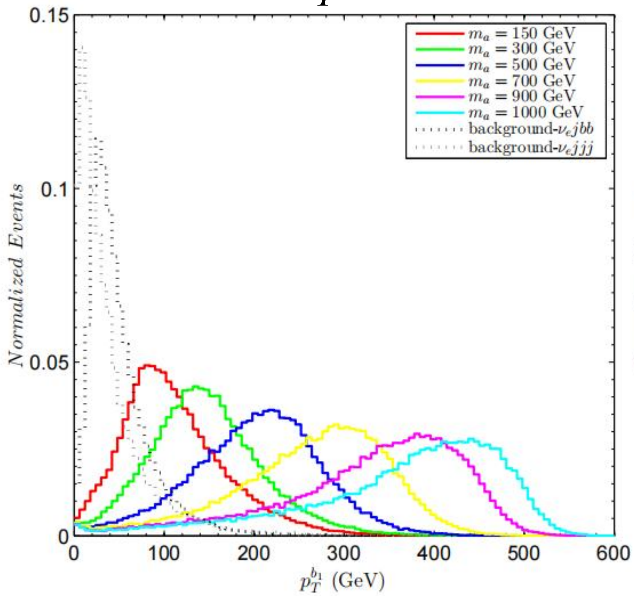




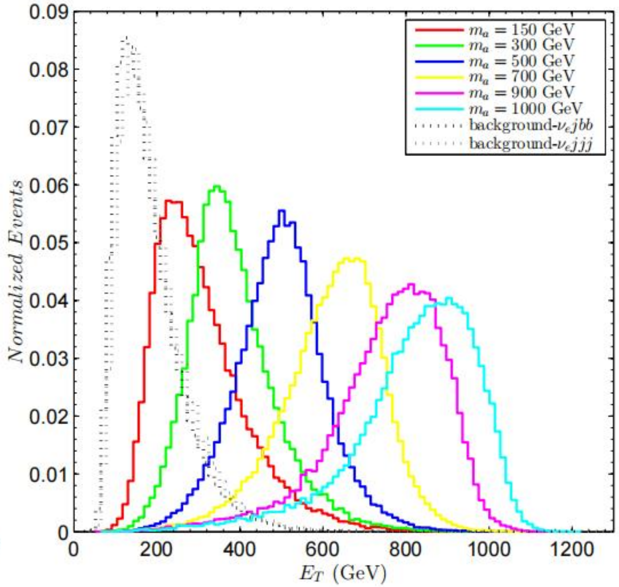
P_T^{bb}

- $100\,\mathrm{GeV} < m_a \leq 1000\,\mathrm{GeV}$

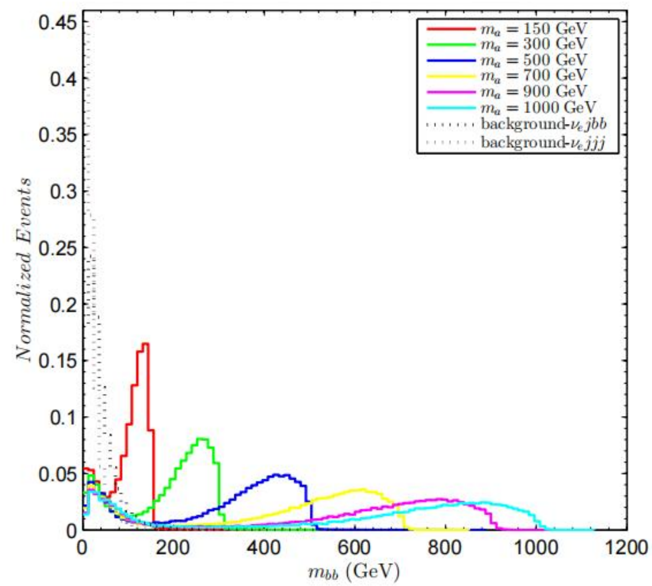
$P_T^{b_1}$



E_T



m_{bb}



- The improved cuts

Cuts	Mass	
	$15\ \text{GeV} \leq m_a \leq 100\ \text{GeV}$	$100\ \text{GeV} < m_a \leq 1000\ \text{GeV}$
Cut 1	$N_b \geq 2,\ N_j \geq 1$	$N_b \geq 2,\ N_j \geq 1$
Cut 2	$m_{bb} > 10\ \text{GeV}$	$p_T^{b_1} > 85\ \text{GeV}$
Cut 3	$p_T^{b_1} > 30\ \text{GeV}$	$E_T > 200\ \text{GeV}$
Cut 4	$\theta_{bb} < 2.9$	$m_{bb} > 100\ \text{GeV}$
Cut 5	$p_T^{bb} > 40\ \text{GeV}$	$-$

Cuts	cross sections for signal (background1, background2) [pb]					
	m_a = 15 GeV	m_a = 30 GeV	m_a = 50 GeV	m_a = 70 GeV	m_a = 90 GeV	m_a = 100 GeV
Basic Cuts	6.1000×10^{-5} $(0.0490, 6.2968)$	1.5831×10^{-3} $(0.0490, 6.2968)$	2.8332×10^{-3} $(0.0490, 6.2968)$	3.0975×10^{-3} $(0.0490, 6.2968)$	3.1289×10^{-3} $(0.0490, 6.2968)$	3.1248×10^{-3} $(0.0490, 6.2968)$
Cut 1	2.8250×10^{-5} $(0.0271, 0.0922)$	8.1835×10^{-4} $(0.0271, 0.0922)$	1.5797×10^{-3} $(0.0271, 0.0922)$	1.8036×10^{-3} $(0.0271, 0.0922)$	1.8604×10^{-3} $(0.0271, 0.0922)$	1.8691×10^{-3} $(0.0271, 0.0922)$
Cut 2	2.2980×10^{-5} $(0.0231, 0.0576)$	7.7615×10^{-4} $(0.0231, 0.0576)$	1.4986×10^{-3} $(0.0231, 0.0576)$	1.7120×10^{-3} $(0.0231, 0.0576)$	1.7665×10^{-3} $(0.0231, 0.0576)$	1.7751×10^{-3} $(0.0231, 0.0576)$
Cut 3	1.9960×10^{-5} $(0.0177, 0.0387)$	7.4325×10^{-4} $(0.0177, 0.0387)$	1.4409×10^{-3} $(0.0177, 0.0387)$	1.6500×10^{-3} $(0.0177, 0.0387)$	1.7096×10^{-3} $(0.0177, 0.0387)$	1.7228×10^{-3} $(0.0177, 0.0387)$
Cut 4	1.7110×10^{-5} $(9.9450 \times 10^{-3}, 0.0250)$	6.1904×10^{-4} $(9.9450 \times 10^{-3}, 0.0250)$	1.1660×10^{-3} $(9.9450 \times 10^{-3}, 0.0250)$	1.3126×10^{-3} $(9.9450 \times 10^{-3}, 0.0250)$	1.3244×10^{-3} $(9.9450 \times 10^{-3}, 0.0250)$	1.3193×10^{-3} $(9.9450 \times 10^{-3}, 0.0250)$
Cut 5	1.6290×10^{-5} $(8.9469 \times 10^{-3}, 0.0220)$	6.1644×10^{-4} $(8.9469 \times 10^{-3}, 0.0220)$	1.1534×10^{-3} $(8.9469 \times 10^{-3}, 0.0220)$	1.2712×10^{-3} $(8.9469 \times 10^{-3}, 0.0220)$	1.2725×10^{-3} $(8.9469 \times 10^{-3}, 0.0220)$	1.2629×10^{-3} $(8.9469 \times 10^{-3}, 0.0220)$
SS	0.093	3.468	6.434	7.078	7.084	7.032

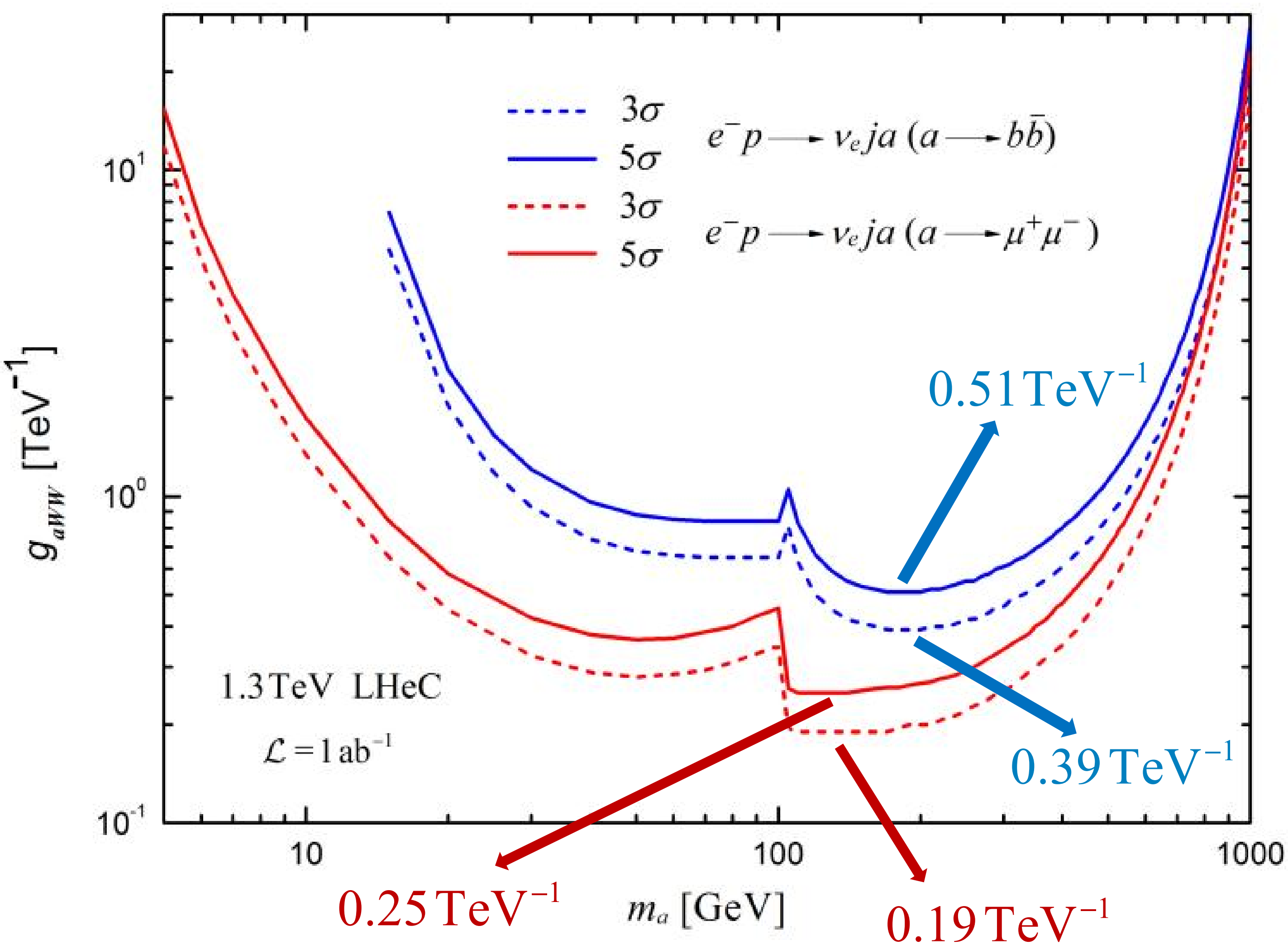
Cuts	cross sections for signal (background1, background2) [pb]					
	m_a = 150 GeV	m_a = 300 GeV	m_a = 500 GeV	m_a = 700 GeV	m_a = 900 GeV	m_a = 1000 GeV
Basic Cuts	2.8355×10^{-3} $(0.0490, 6.2968)$	1.3969×10^{-3} $(0.0490, 6.2968)$	3.8331×10^{-4} $(0.0490, 6.2968)$	6.6391×10^{-5} $(0.0490, 6.2968)$	4.9981×10^{-6} $(0.0490, 6.2968)$	7.7509×10^{-7} $(0.0490, 6.2968)$
Cut 1	1.7067×10^{-3} $(0.0271, 0.0922)$	8.2443×10^{-4} $(0.0271, 0.0922)$	2.1850×10^{-4} $(0.0271, 0.0922)$	3.6355×10^{-5} $(0.0271, 0.0922)$	2.5790×10^{-6} $(0.0271, 0.0922)$	3.8905×10^{-7} $(0.0271, 0.0922)$
Cut 2	1.0934×10^{-3} $(3.5966 \times 10^{-3}, 9.6278 \times 10^{-3})$	6.9825×10^{-4} $(3.5966 \times 10^{-3}, 9.6278 \times 10^{-3})$	2.0489×10^{-4} $(3.5966 \times 10^{-3}, 9.6278 \times 10^{-3})$	3.4825×10^{-5} $(3.5966 \times 10^{-3}, 9.6278 \times 10^{-3})$	2.4991×10^{-6} $(3.5966 \times 10^{-3}, 9.6278 \times 10^{-3})$	3.7804×10^{-7} $(3.5966 \times 10^{-3}, 9.6278 \times 10^{-3})$
Cut 3	1.0447×10^{-3} $(2.7793 \times 10^{-3}, 7.7577 \times 10^{-3})$	6.9545×10^{-4} $(2.7793 \times 10^{-3}, 7.7577 \times 10^{-3})$	2.0480×10^{-4} $(2.7793 \times 10^{-3}, 7.7577 \times 10^{-3})$	3.4825×10^{-5} $(2.7793 \times 10^{-3}, 7.7577 \times 10^{-3})$	2.4991×10^{-6} $(2.7793 \times 10^{-3}, 7.7577 \times 10^{-3})$	3.7804×10^{-7} $(2.7793 \times 10^{-3}, 7.7577 \times 10^{-3})$
Cut 4	7.8474×10^{-4} $(8.1555 \times 10^{-4}, 8.8780 \times 10^{-4})$	5.9819×10^{-4} $(8.1555 \times 10^{-4}, 8.8780 \times 10^{-4})$	1.7398×10^{-4} $(8.1555 \times 10^{-4}, 8.8780 \times 10^{-4})$	2.9176×10^{-5} $(8.1555 \times 10^{-4}, 8.8780 \times 10^{-4})$	2.0992×10^{-6} $(8.1555 \times 10^{-4}, 8.8780 \times 10^{-4})$	3.1304×10^{-7} $(8.1555 \times 10^{-4}, 8.8780 \times 10^{-4})$
SS	15.728	12.461	4.012	0.701	0.050	0.008

a tagging efficiency of 75% for b jets

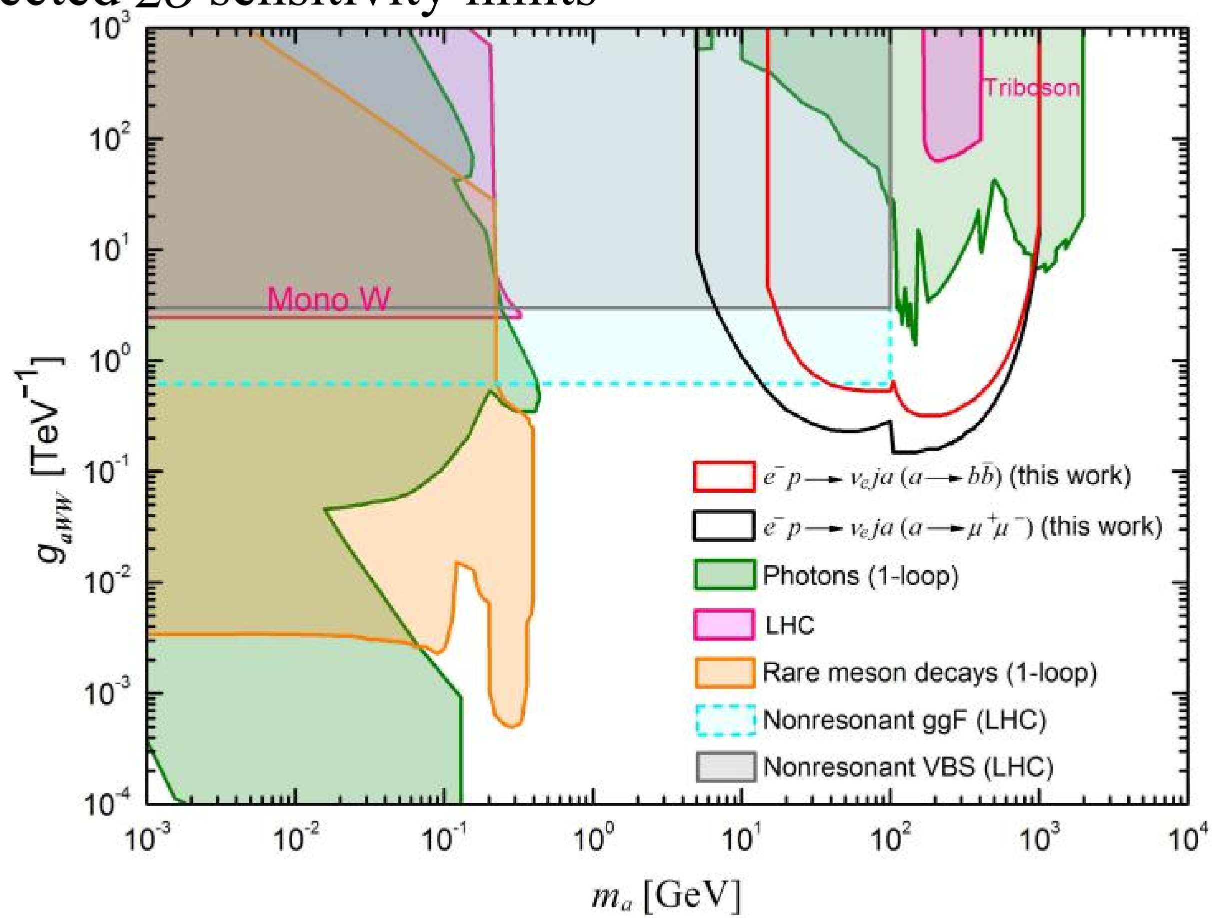
a mistagging rate of 5% for c jets

a mistagging rate of 0.1% for other light flavor jets

- $g_{aWW} = 1\,\mathrm{TeV}^{-1}$


3σ
5σ
3σ
5σ
$e^-p \to \nu_e j a\ (a \to b\bar{b})$
$e^-p \to \nu_e j a\ (a \to \mu^+\mu^-)$
1.3TeV LHeC
$\mathcal{L} = 1\,\mathrm{ab}^{-1}$
g_{aWW} [TeV^{-1}]
m_a [GeV]
0.51 TeV^{-1}
0.39 TeV^{-1}
0.25 TeV^{-1}
0.19 TeV^{-1}

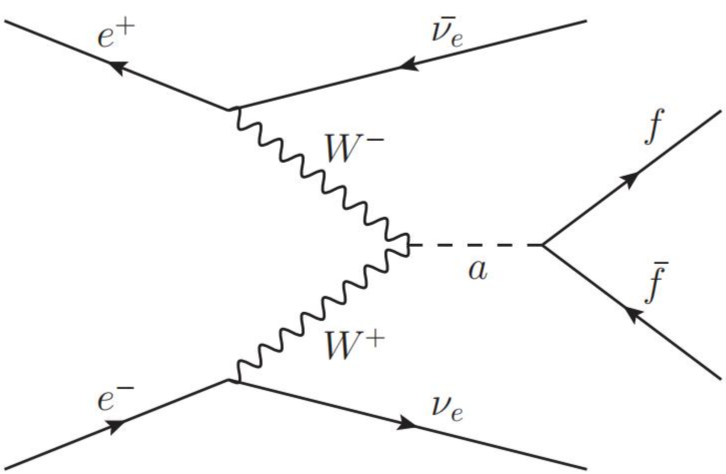
- The projected 2σ sensitivity limits



- $e^- p \to \nu_e ja(a \to \mu^+\mu^-)$ ⟶ $m_a \in [14, 924]$ GeV $\quad g_{aWW} \in [0.15, 6.66]\,\text{TeV}^{-1}$
- $e^- p \to \nu_e ja(a \to b\bar{b})$ ⟶ $m_a \in [39, 900]$ GeV $\quad g_{aWW} \in [0.32, 6.67]\,\text{TeV}^{-1}$

Liaoning Normal University

Phys.Lett.B 848 (2024) 138368 **Chong-Xing Yue, Han Wang***, Yue-Qi Wang



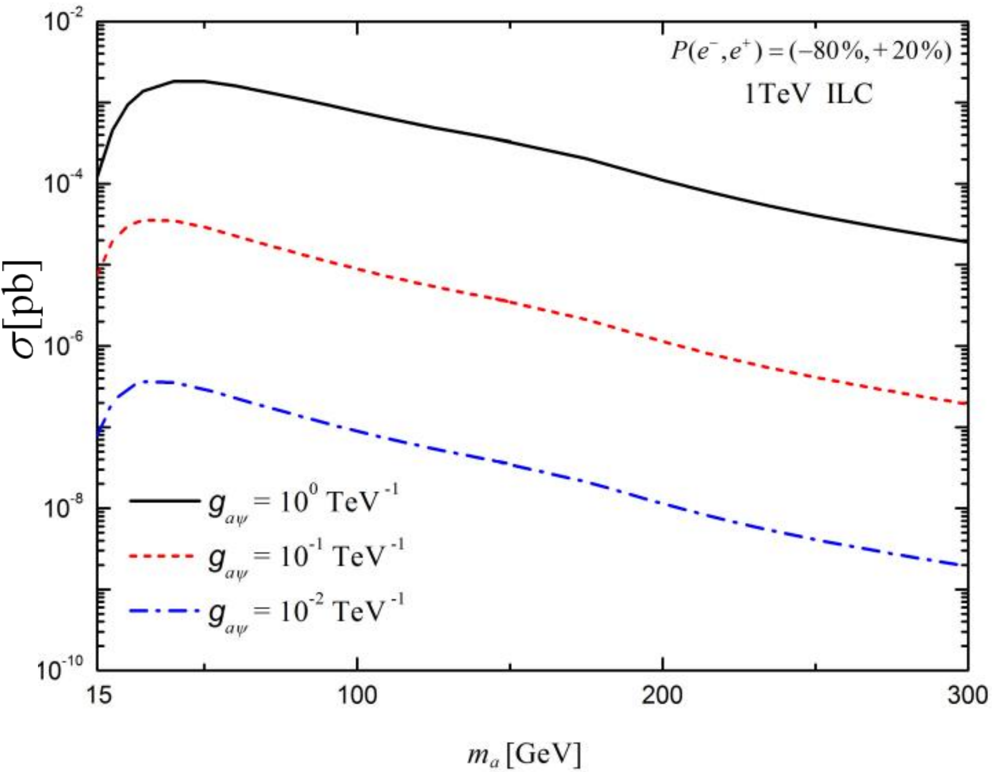
- $\nu_e \bar{\nu}_e t \bar{t}$ → unclean backgrounds

$$m_a < 2m_t$$

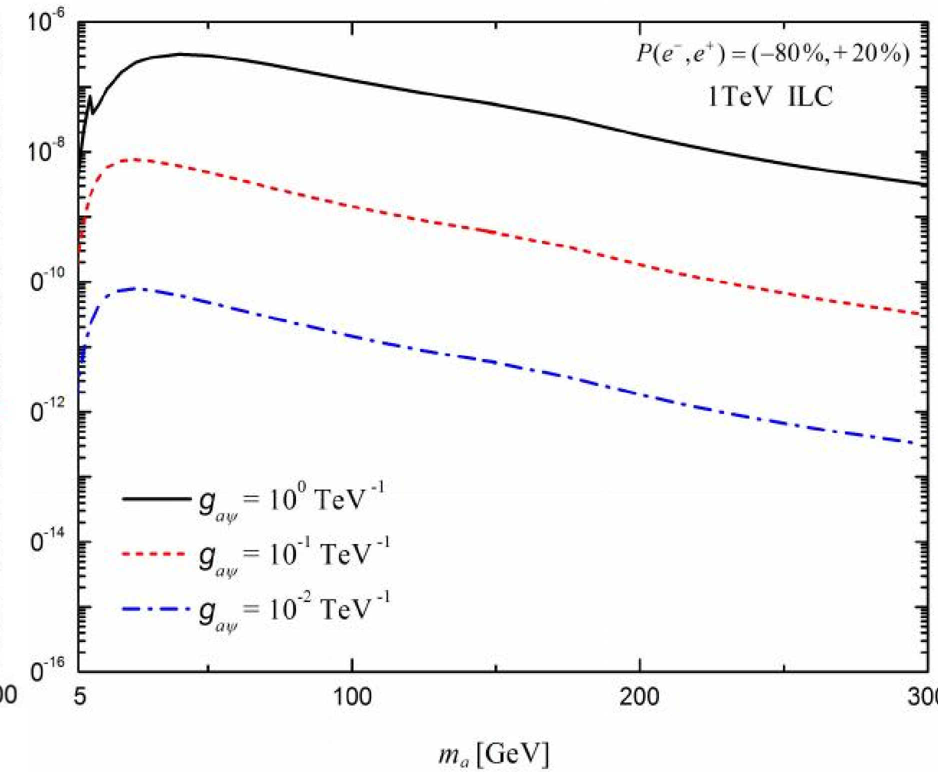
$\nu_e \bar{\nu}_e c \bar{c}$

$\nu_e \bar{\nu}_e \tau^+ \tau^-$

} not tagged efficiently



$$e^-e^+ \to \nu_e \overline{\nu_e} a(a \to b\bar{b})$$



$$e^-e^+ \to \nu_e \overline{\nu_e} a(a \to \mu^+\mu^-)$$

- Phys.Rev.D 104 (2021) 9, 092005, 2106.10085

↓

$$g_{aWW} = 0.62\text{TeV}^{-1}$$

- ILC

$$E_{CM} = 1\ \text{TeV}$$

$$\mathcal{L} = 1\ \text{ab}^{-1}$$

$$P(e^-, e^+) = (-80\%, +20\%)$$

- Basic cuts:

$$P_T^b > 5\ \text{GeV}$$

$$P_T^l > 20\ \text{GeV}$$

$$|\eta_b| < 2.5 \qquad |\eta_j| < 5$$

$$\Delta R_{bb} > 0.4 \quad \Delta R_{jj} > 0.4$$

- $15\,\text{GeV} \le m_a \le 50\,\text{GeV}$

observables:

the invariant mass m_{bb}

the cone size ΔR_{bb}

the missing transverse energy $\not{E}_T$

the angular separation $\Delta\theta_{bb}$

- $50\,\text{GeV} < m_a \le 300\,\text{GeV}$

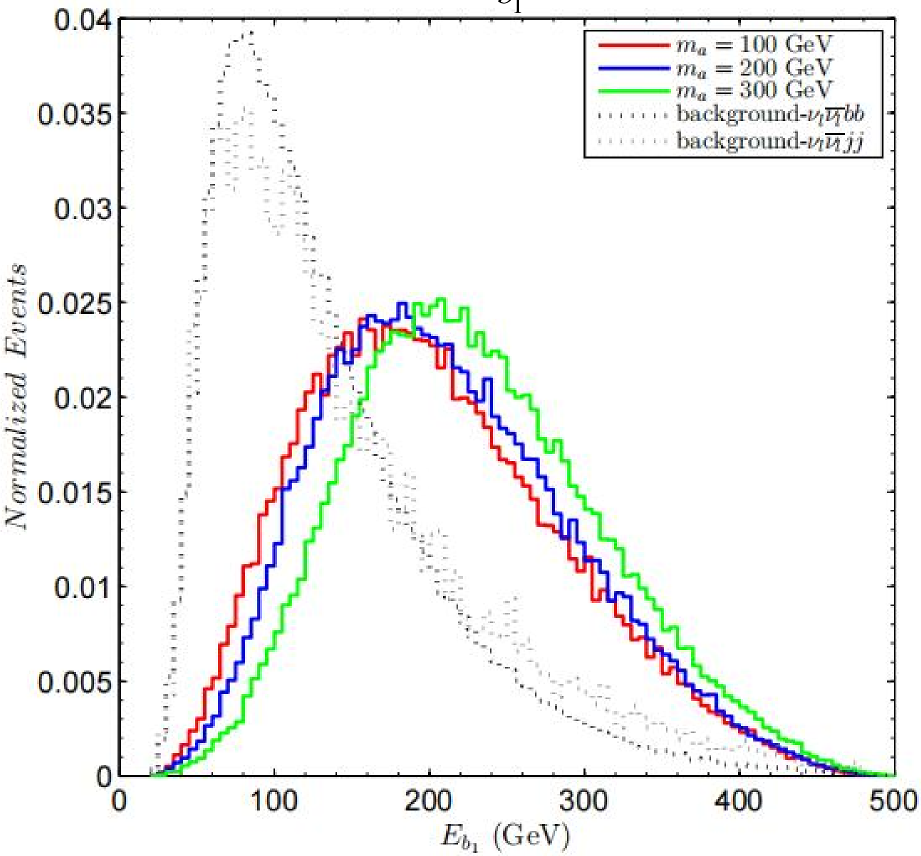
observables:

the energy of the hardest b-jet E^{b_1}

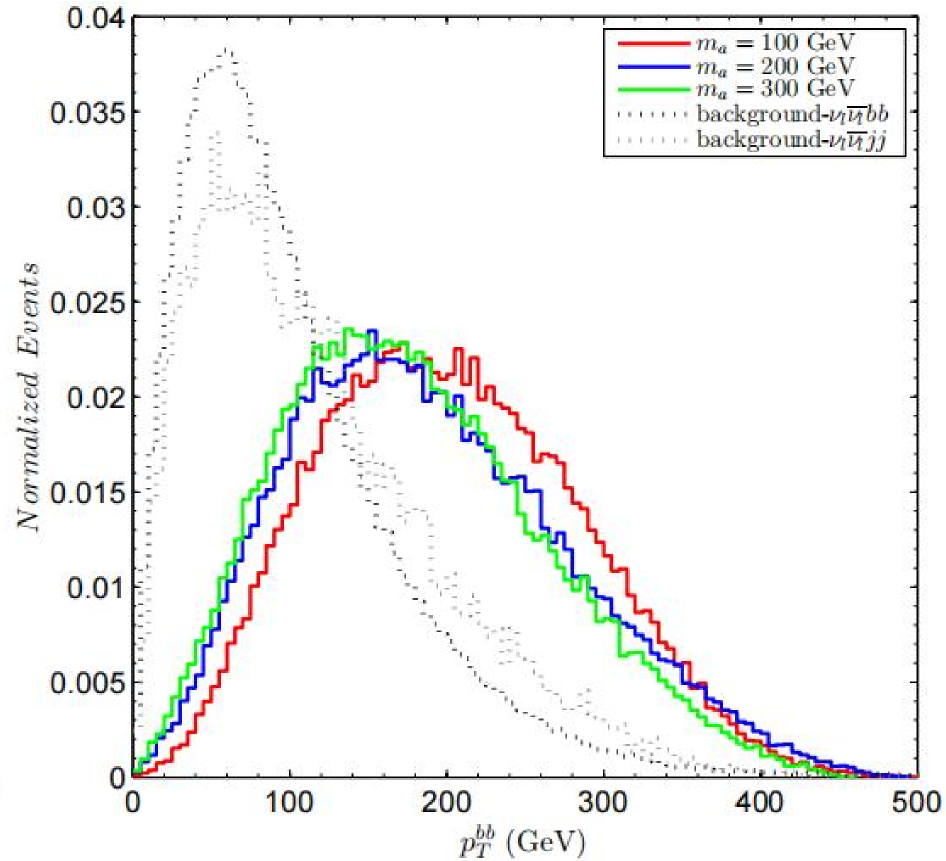
the transverse momentum of the reconstructed ALP P_T^{bb}

- $50\,\mathrm{GeV} < m_a \leq 300\,\mathrm{GeV}$

E_{b_1}



P_T^{bb}

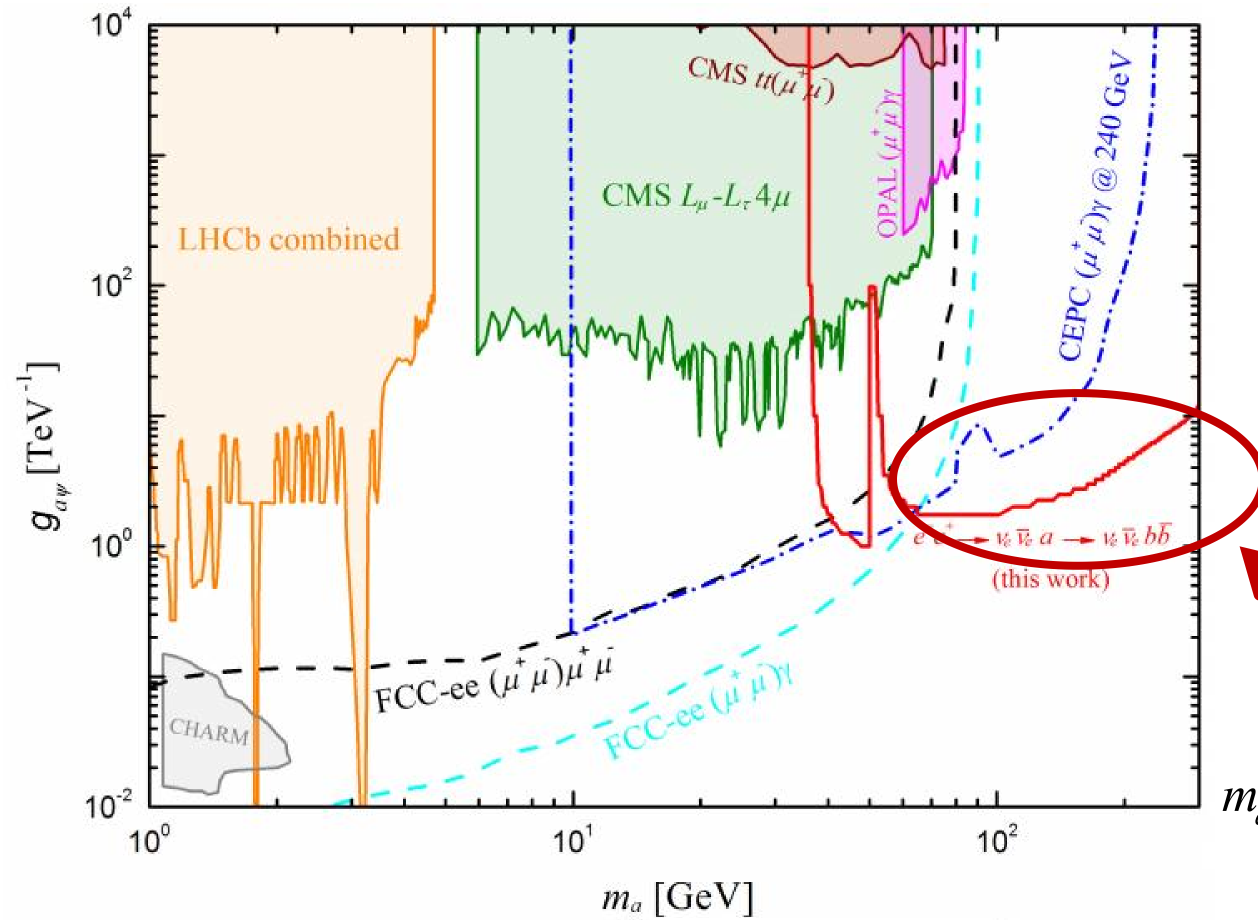


- The improved cuts

Cuts	Mass	
	$15\ \text{GeV} \leq m_a \leq 50\ \text{GeV}$	$50\ \text{GeV} < m_a \leq 300\ \text{GeV}$
Cut 1	$N_b \geq 2$	$N_b \geq 2$
Cut 2	$m_{bb} < 80\ \text{GeV}$	$E_{b_1} > 120\ \text{GeV}$
Cut 3	$\Delta R_{bb} < 1$	$p_T^{bb} > 100\ \text{GeV}$
Cut 4	$\not{E}_T > 40\ \text{GeV}$	–
Cut 5	$\Delta\theta_{bb} < 0.8$	–

Cuts	Cross sections for signal (bg-$\nu_l\overline{\nu_l}b\bar{b}$, bg-$\nu_l\overline{\nu_l}jj$) [pb]		
	$m_a = 100$ GeV	$m_a = 200$ GeV	$m_a = 300$ GeV
Basic Cuts	5.4310×10^{-3} (0.6889, 0.8857)	3.1891×10^{-3} (0.6889, 0.8857)	1.0866×10^{-3} (0.6889, 0.8857)
Cut 1	1.6686×10^{-3} $(0.1809, 4.3155 \times 10^{-3})$	1.3018×10^{-3} $(0.1809, 4.3155 \times 10^{-3})$	4.9840×10^{-4} $(0.1809, 4.3155 \times 10^{-3})$
Cut 2	1.3973×10^{-3} $(0.0835, 2.1934 \times 10^{-3})$	1.1422×10^{-3} $(0.0835, 2.1934 \times 10^{-3})$	4.6240×10^{-4} $(0.0835, 2.1934 \times 10^{-3})$
Cut 3	1.3170×10^{-3} $(0.0535, 1.6275 \times 10^{-3})$	1.0191×10^{-3} $(0.0535, 1.6275 \times 10^{-3})$	3.9370×10^{-4} $(0.0535, 1.6275 \times 10^{-3})$
SS	5.545	4.300	1.671

- $g_{a\Psi} = 10\,\mathrm{TeV}^{-1}$



- $m_a \in [37, 50]$ GeV $\longrightarrow$ $g_{a\Psi} \to 1\,\text{TeV}^{-1}$

  $m_a \in [52, 300]$ GeV $\longrightarrow$ $g_{a\Psi} \to 1.75\,\text{TeV}^{-1}$

- ALP appears naturally in broad extensions of the SM, which have various beneficial properties to search by many high energy experiments

- The promising sensitivities of the 240 GeV CEPC to the coupling $g_{a\gamma\gamma}$ are in the range of $0.0325\,\text{TeV}^{-1}$ to $0.037\,\text{TeV}^{-1}$ with m_a from 2.9 GeV to 190 GeV

- The 1.3 TeV LHeC is more sensitive to the coupling g_{aWW} via the W^+W^- fusion processes $e^-p \to \nu_e ja(a \to \mu^+\mu^-)$ and $e^-p \to \nu_e ja(a \to b\bar{b})$ for ALP with the mass range of roughly a few tens to 900 GeV

- The currently unconstrained $m_a - g_{a\Psi}$ parameter space can be covered by the 1 TeV ILC, for which the corresponding reaches are $1\,\text{TeV}^{-1}$ and $1.75\,\text{TeV}^{-1}$ from $37\,\text{GeV} \le m_a \le 50\,\text{GeV}$ and $52\,\text{GeV} \le m_a \le 300\,\text{GeV}$, respectively

Searching for axion-like particles at future e^+e^- and e^-p colliders

Thanks

Han Wang (王晗)

Liaoning Normal University

27th Mini-workshop on the frontier of LHC

2024.01.22