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Reason is The Only Truth, The Best Good And The Farthest

Photophobic ALPs at hadron colliders

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In collaboration with Zilong Ding, Yingnan Mao, Kechen Wang, Yiheng Xiong

1. [Zilong Ding, Yingnan Mao, Kechen Wang, Search for the γZ decay mode of heavy photophobic axion-like particles at the LHC, JHEP 06 (2025) 087]
2. [Yingnan Mao, Kechen Wang, Yiheng Xiong, Sensitivities of new resonance couplings to W-bosons at the LHC, Chin.Phys. 49 (2025) 8, 083106]
3. [Jiaojiao Feng, Yingnan Mao, Kechen Wang, Discovery prospects for photophobic ALPs in the $WWjj$ final state at the HL-LHC, Chin.Phys.C 50 (2026) 6, 063107]
4. [Zilong Ding, Jiaojiao Feng, Yingnan Mao, et.al, Discovery prospects for photophobic axion-like particles at a 100 TeV proton-proton collider, arXiv:2512.23155]

01. Theoretical Framework

02. Photophobic ALPs at hadron colliders

03. Summary and Conclusion

Strong CP problem

- Strong CP problem:

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{QCD}} + \bar{\theta} \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{\mu\nu a}$$

- Neutron electric dipole moment:

$$d_n = e\bar{\theta}C_{\text{EDM}} \leq 1.8 \times 10^{-26} e \cdot \text{cm} \implies \bar{\theta} < 10^{-10}$$

- Peccei–Quinn Mechanism:

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{QCD}} + \frac{1}{2} \partial_\mu a \partial^\mu a + \left(\bar{\theta} + \frac{a}{f_a} \right) \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{\mu\nu a}$$
$$a = -\bar{\theta} f_a$$
$$\bar{\theta} + \frac{a}{f_a} = 0$$

*Based on,

[Abel, C. et.al, Measurement of the Permanent Electric Dipole Moment of the Neutron, Phys.Rev.Lett. 124 (2020) 8, 081803]

[Baker, C. A. et.al, An Improved experimental limit on the electric dipole moment of the neutron Nucl.Phys.A 844 (2010) 47c-52c]

- The ALP Lagrangian(dimension-five):

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - c_{\tilde{W}} \frac{a}{f_a} W_{\mu\nu}^a \tilde{W}^{a\mu\nu} - c_{\tilde{B}} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

- After electroweak symmetry breaking, ALPs interactions with gauge bosons :

$$\mathcal{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{2} g_{aZ\gamma} a Z_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{4} g_{aZZ} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{1}{4} g_{aWW} a W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}$$

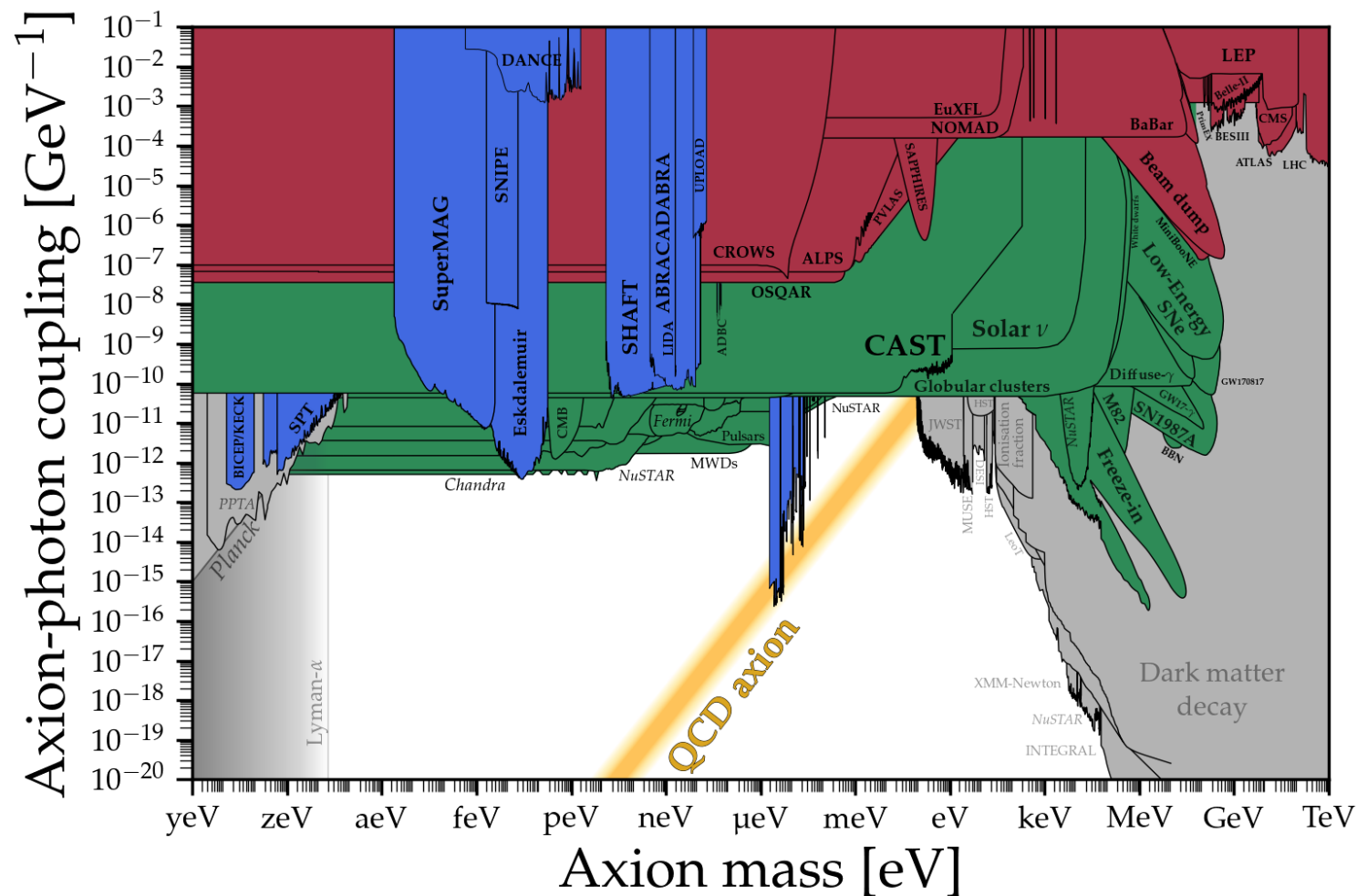
- The couplings between ALP and gauge bosons :

$$g_{a\gamma\gamma} = \frac{4}{f_a} (s_\theta^2 c_{\tilde{W}} + c_\theta^2 c_{\tilde{B}}) \qquad g_{aZZ} = \frac{4}{f_a} (c_\theta^2 c_{\tilde{W}} + s_\theta^2 c_{\tilde{B}})$$

$$g_{a\gamma Z} = \frac{2}{f_a} s_{2\theta} (c_{\tilde{W}} - c_{\tilde{B}}) \qquad g_{aWW} = \frac{4}{f_a} c_{\tilde{W}}$$

Experiment limits

- Stringent constraints on $g_{a\gamma\gamma}$
- Across a broad ALP mass range



- Motivation: Search for ALPs with suppressed diphoton couplings

➤ Photophobic axion-like particles

$$g_{a\gamma\gamma} = \frac{4}{f_a} (s_\theta^2 c_{\tilde{W}} + c_\theta^2 c_{\tilde{B}}) = 0$$



$$\frac{c_{\tilde{B}}}{c_{\tilde{W}}} = -\frac{s_\theta^2}{c_\theta^2} = -t_\theta^2$$

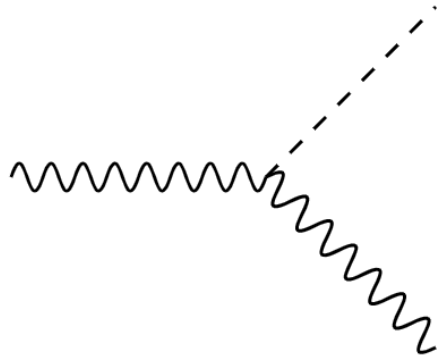
$$g_{aWW} = \frac{4}{f_a} c_{\tilde{W}}$$

$$g_{aZZ} = \frac{4}{f_a} (c_\theta^2 c_{\tilde{W}} + s_\theta^2 c_{\tilde{B}}) = (1 - t_\theta^2) g_{aWW}$$

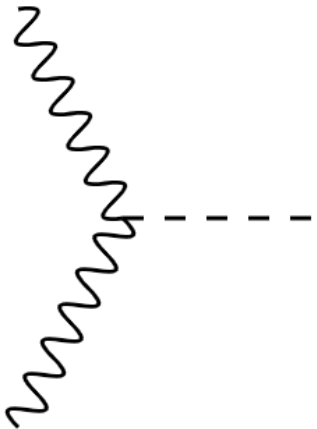
$$g_{a\gamma Z} = \frac{2}{f_a} s_{2\theta} (c_{\tilde{W}} - c_{\tilde{B}}) = t_\theta g_{aWW}$$

Production and Decay

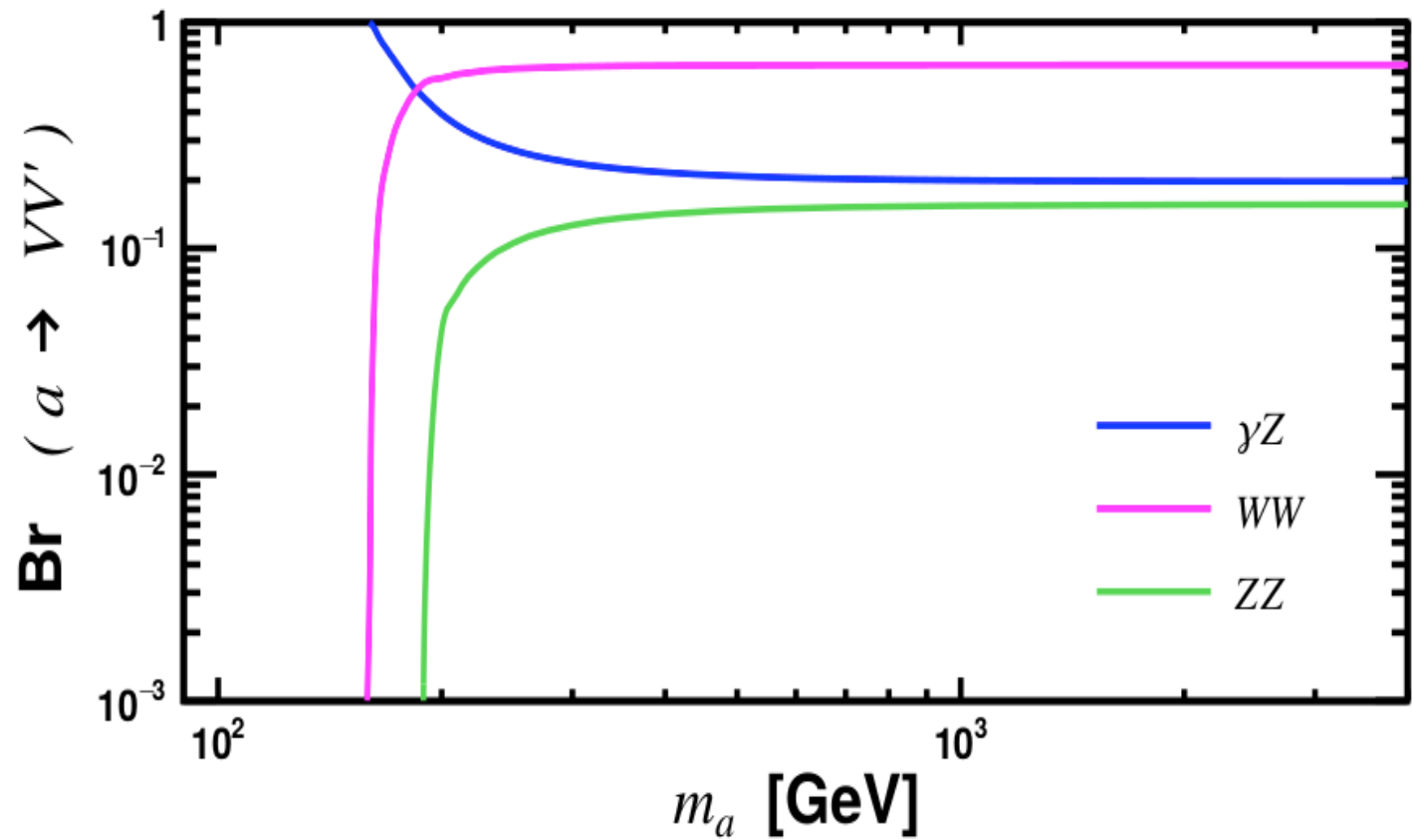
➤ ALP-associated production with a boson



➤ Vector Boson Fusion



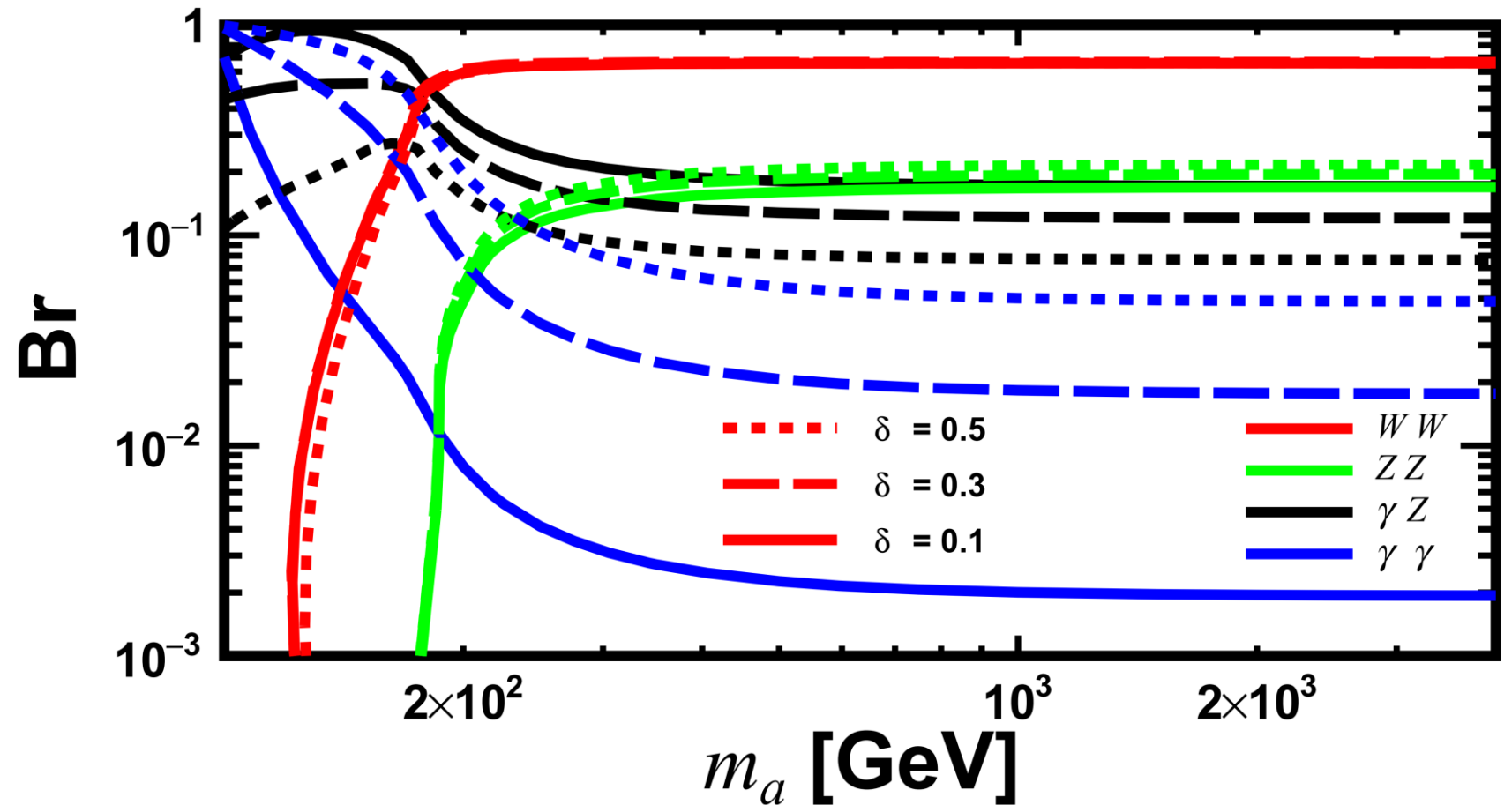
☞ Decay mode



Assuming

➤ Photophobic deviations

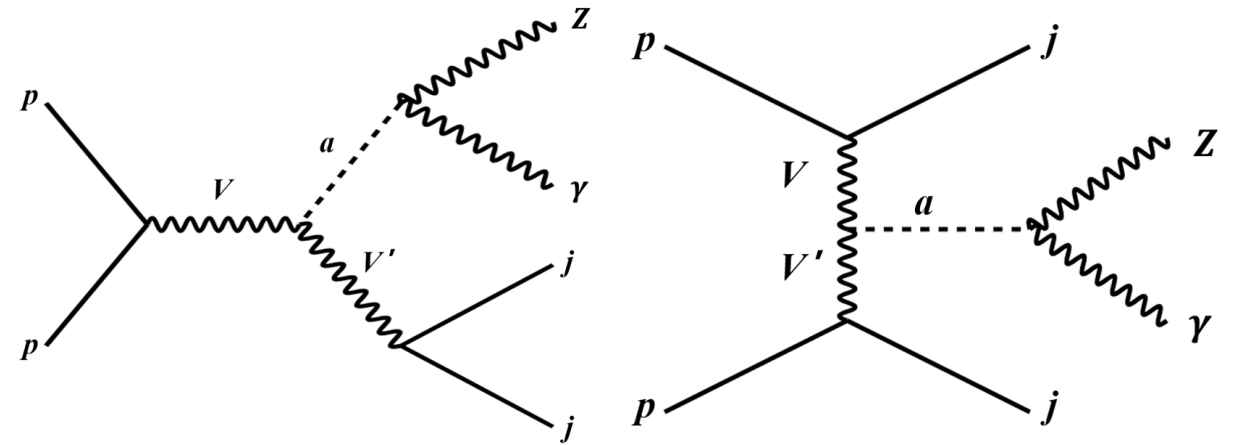
$$\frac{c_{\tilde{B}}}{c_{\tilde{W}}} = -t_{\theta}^2 + \delta$$
$$g_{a\gamma\gamma} = g_{aWW} c_{\theta}^2 \delta$$



$$p p \rightarrow j j a(\rightarrow \gamma Z)$$

$$V = \gamma, Z, W$$

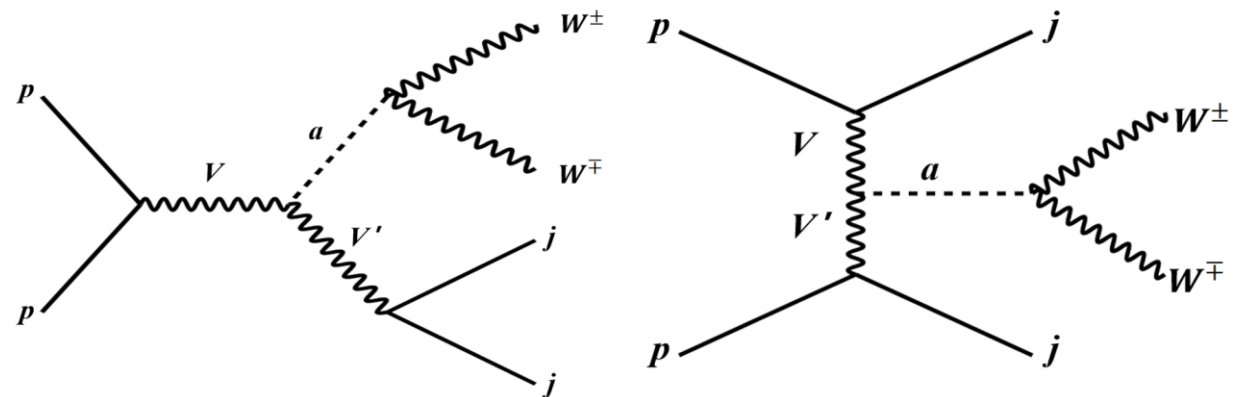
$$V' = Z, W$$



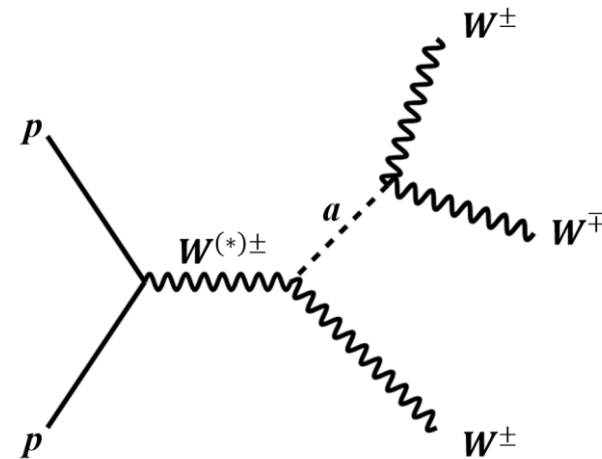
$$p p \rightarrow j j a(\rightarrow W^{\pm} W^{\mp})$$

$$V = \gamma, Z, W$$

$$V' = Z, W$$



$$p p \rightarrow W^{\pm} a(\rightarrow W^{\pm} W^{\mp})$$



MadGraph 5

generate Feynman diagrams

calculate the cross-sections

produces parton-level data

PYTHIA 8

particle decay

shower

hadronization

Delphes 3

detector simulation

◆ **Background:** $\oplus W^{\pm} W^{\mp} j j$

$$\oplus W^{\pm} Z j j$$

$$\oplus Z Z j j$$

$$\oplus Z(\rightarrow l^{\pm} l^{\mp}) j j$$

$$\oplus W^{\pm}(\rightarrow l^{\pm} \nu) j j$$

$$\oplus t \bar{t}$$

◆ **Preselection:**

- $N(l) = 2;$
- $p_T(l) > 10 \text{ GeV};$
- $N(\mu) = 1; N(e) = 1;$
- $Q(e) + Q(\mu) = 0;$
- $N(j) \geq 2;$
- $p_T(j_1), p_T(j_2) > 30 \text{ GeV};$
- $N(j_b) = 0.$

◆ Multivariate analysis:

➤ input observables:

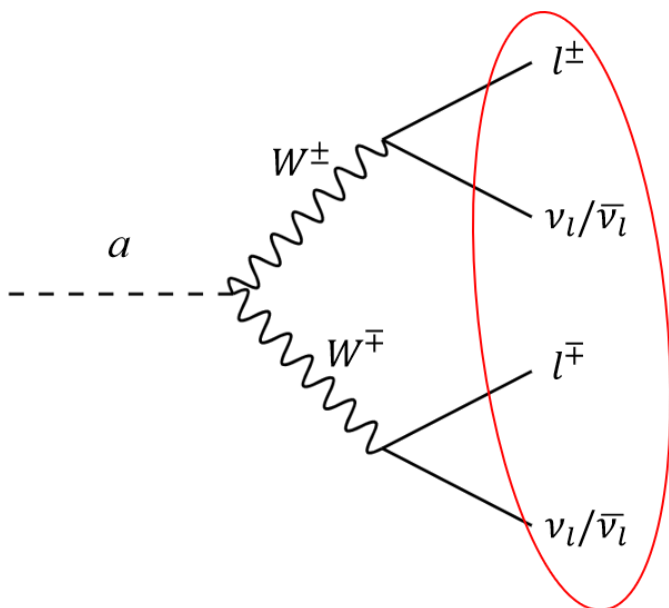
momentum and energy

reconstructed invariant mass

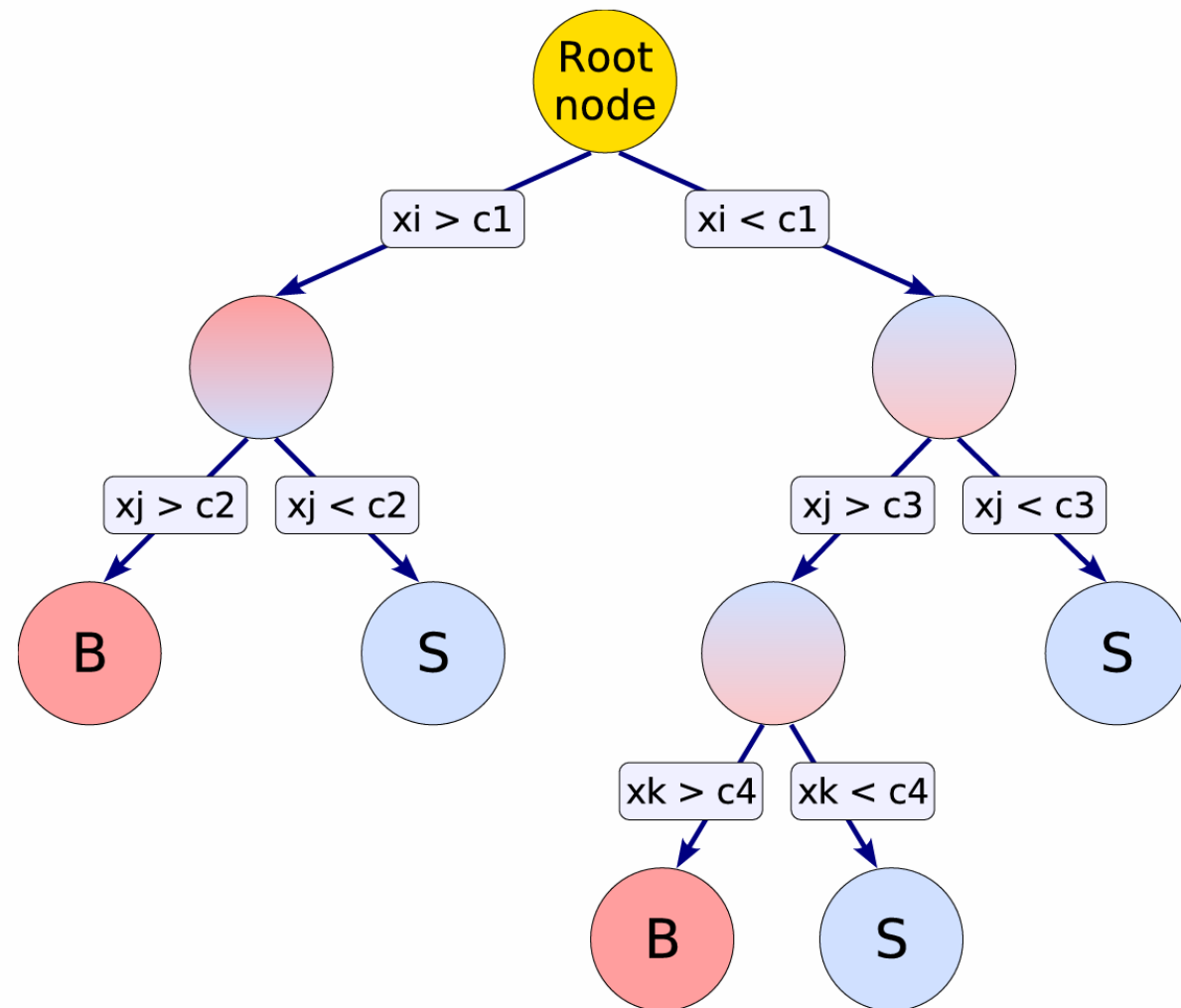
angular separations ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$)

.....

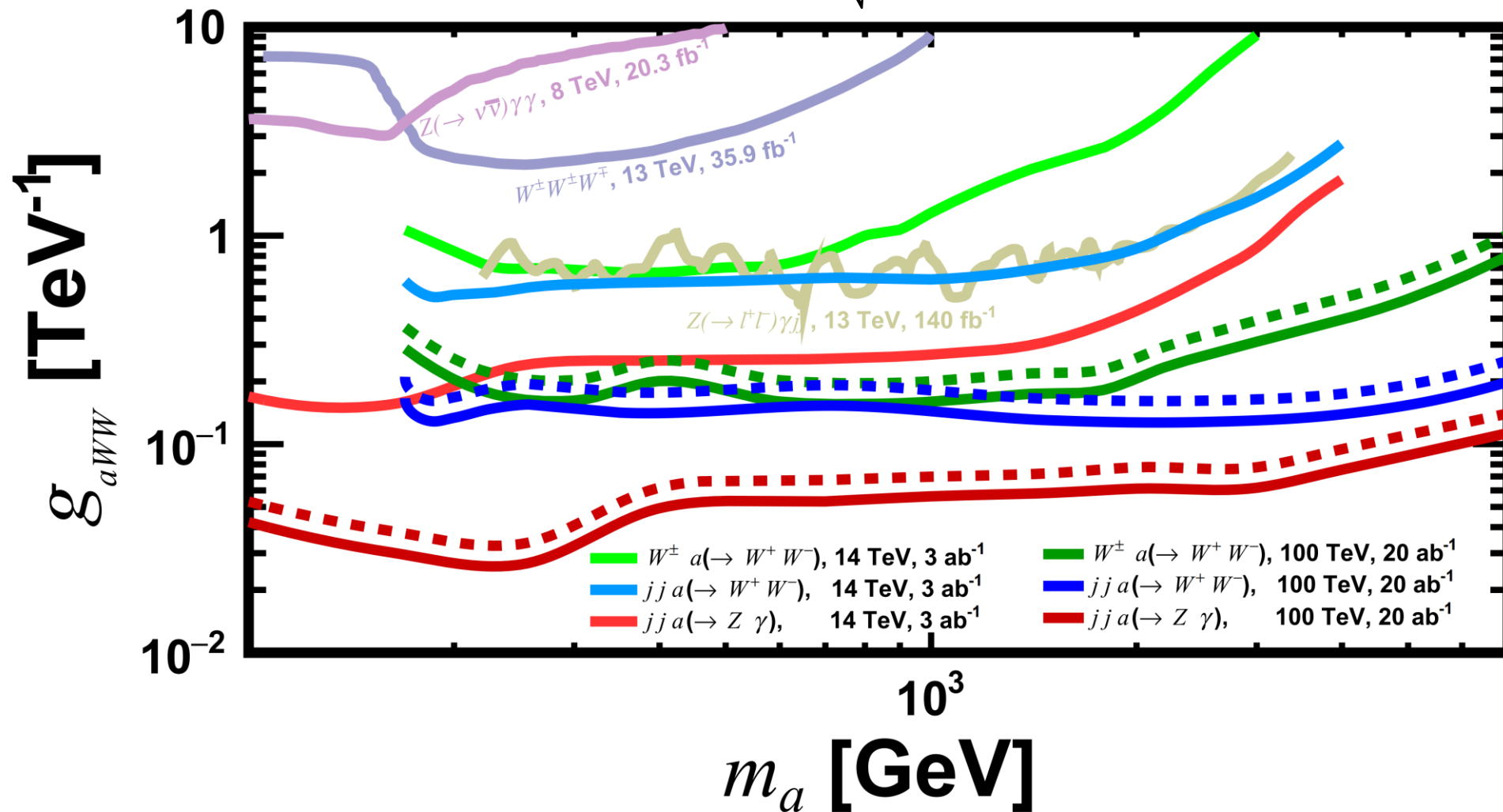
.....



➤ Boosted Decision Tree (BDT):



$$\sigma = \sqrt{2 \left[(N_s + N_b) \ln \left(1 + \frac{N_s}{N_b} \right) - N_s \right]}$$

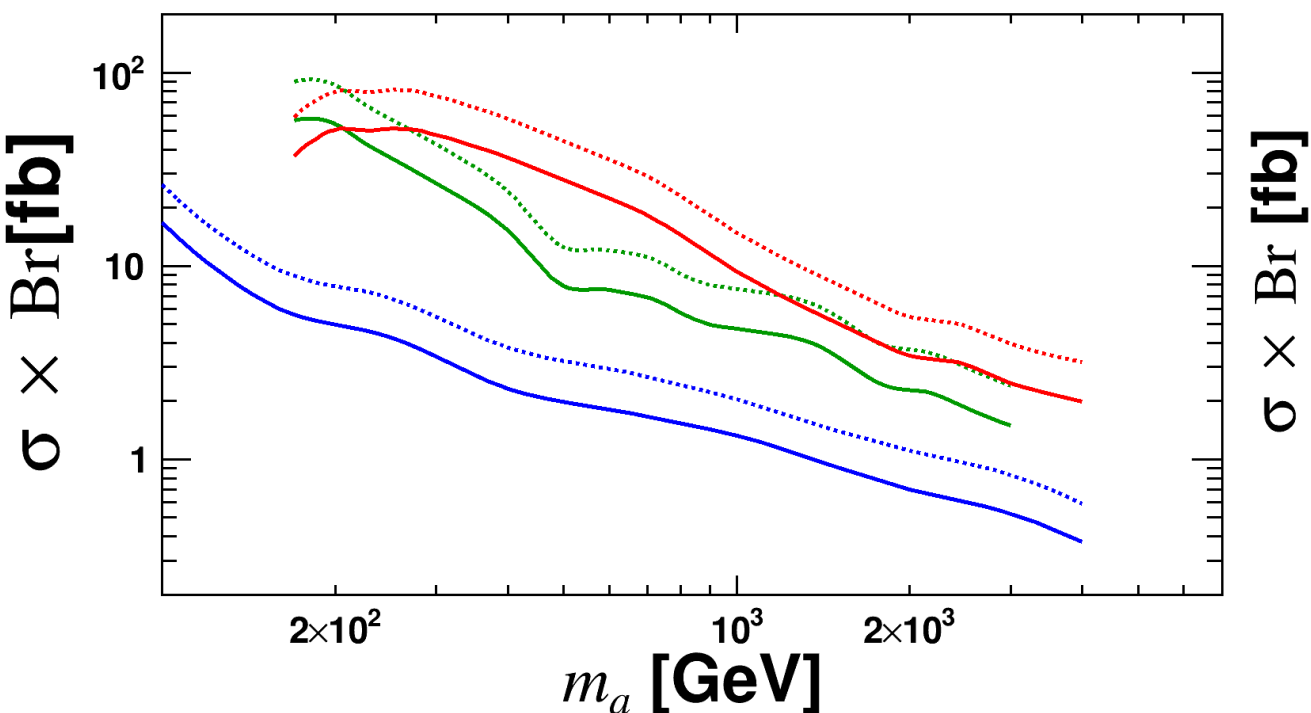


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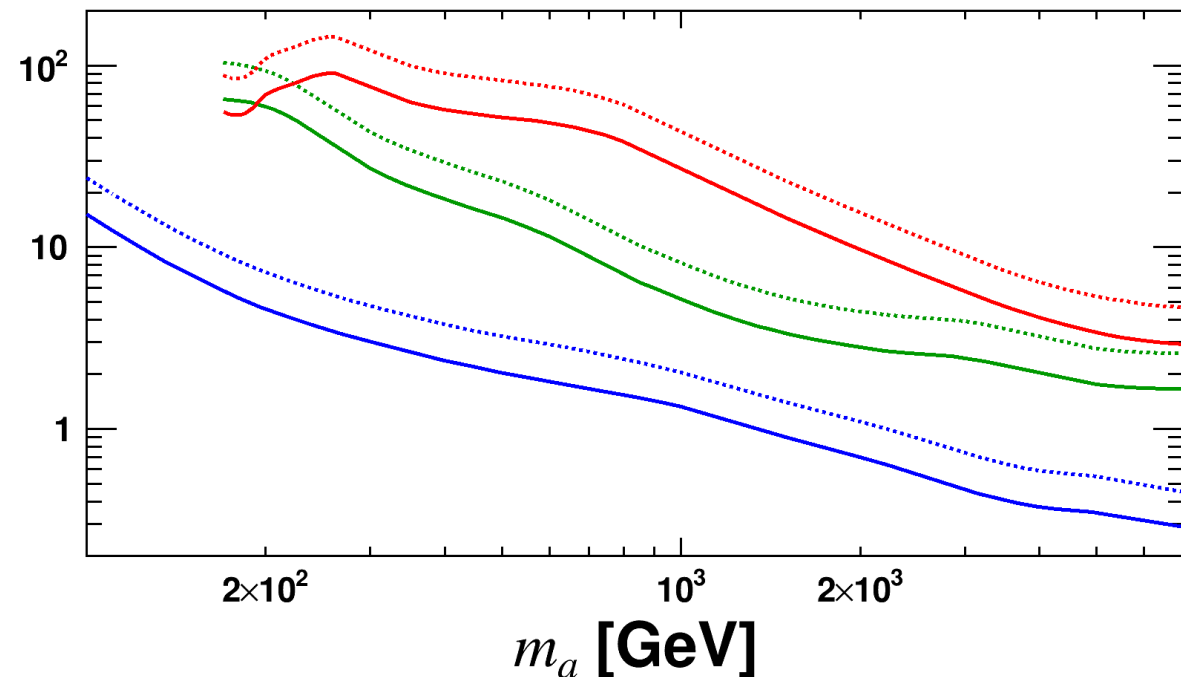
Discovery Sensitivities $\sigma \times \text{Br}$

- 2- σ , $\sigma(p p \rightarrow j j a) \times \text{Br}(a \rightarrow Z\gamma)$
- ⋯ 5- σ , $\sigma(p p \rightarrow j j a) \times \text{Br}(a \rightarrow Z\gamma)$
- 2- σ , $\sigma(p p \rightarrow j j a) \times \text{Br}(a \rightarrow W^+W^-)$
- ⋯ 5- σ , $\sigma(p p \rightarrow j j a) \times \text{Br}(a \rightarrow W^+W^-)$
- 2- σ , $\sigma(p p \rightarrow W^\pm a) \times \text{Br}(a \rightarrow W^+W^-)$
- ⋯ 5- σ , $\sigma(p p \rightarrow W^\pm a) \times \text{Br}(a \rightarrow W^+W^-)$

14 TeV



100 TeV



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Impact of systematics

$\sqrt{s} = 14 \text{ TeV}$
 $m_a = 750 \text{ GeV}$

$$\sigma_b = \delta_b N_b$$

$$\sigma_{stat+syst} = \sqrt{2 \left[(N_s + N_b) \ln \frac{(N_s + N_b)(N_b + \sigma_b^2)}{N_b^2 + (N_s + N_b)\sigma_b^2} - \frac{N_b^2}{\sigma_b^2} \ln \left(1 + \frac{\sigma_b^2 N_s}{N_b(N_b + \sigma_b^2)} \right) \right]}$$

δ_b	2σ		5σ	
	$g_{aWW}/(\text{TeV}^{-1})$	$\sigma \times \text{Br/fb}$	$g_{aWW}/(\text{TeV}^{-1})$	$\sigma \times \text{Br/fb}$
0%	0.626	16.3	0.788	25.8
2%	0.642	17.1	0.811	27.3
5%	0.847	29.7	1.07	47.9
8%	1.04	45.2	1.33	73.7
10%	1.16	56.3	1.49	92.3

- Photophobic axion-like particles

Theoretical Motivation & Assumptions

- Production

ALP-associated production with a boson & Vector Boson Fusion

- Decay mode

γZ , WW

- Data analyses method

Preselection, Multivariate analysis

- Results

The HL-LHC results provide competitive sensitivities, with additional studies assessing the effects of photophobic deviations and background systematic uncertainties.

A 100 TeV collider significantly extends the ALP discovery reach, with complementary sensitivities from different signal channels.

Model-independent sensitivities in $\sigma \times \text{Br}$ facilitate reinterpretation in other models.



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Thank you!

