ALP one-loop corrections and non-resonant searches

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Based on:

JB, I. Brivio, M.B. Gavela, V. Sanz [2107.11392]

JB, I. Brivio, J. Machado-Rodríguez, J. F. de Trocóniz [2202.03450]

What is an ALP?

ALPs = **A**xion-**L**ike **P**articles

- ALPs are pseudo-Goldstone bosons from breaking of BSM global symmetry
- Derivative and anomalous couplings to SM particles:

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \underbrace{\frac{\partial_\mu a}{f_a}\mathrm{SM}^\mu}_{\text{Derivative}} + \underbrace{\frac{a}{f_a}X_{\mu\nu}\tilde{X}^{\mu\nu}}_{\text{Anomalous}}$$

- Approximate shift symmetry: $a \to a + \theta$
- Predicted by many BSM theories: **axion** (PQ symmetry), **majoron** (dynamical neutrino masses, Lepton number), **flavon** (flavor symmetry), extra dimensions, string theory, etc...
- Under certain conditions, good DM candidate

ALP effective field theory

- dimension-5 **linear effective Lagrangian**:

$$\mathscr{L}_{ALP} = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - c_{\tilde{B}}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{\tilde{W}}\frac{a}{f_a}W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu} - c_{\tilde{G}}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{\partial_\mu a}{f_a}\sum_{\substack{\mathrm{f}=Q_L,\,L_L\\ u_R,\,d_R,\,e_R}} \bar{\mathrm{f}}\gamma^\mu \boldsymbol{c}_{\mathrm{f}}\mathrm{f}$$

- $\boldsymbol{c}_{\mathrm{f}} \to n_g \times n_g$ hermitian matrices in flavor space
- Additional operator: $i\frac{c_{a\Phi}}{f_a}\partial^\mu a\left(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right)$ → EOMs → Redundant
- No tree level coupling to Higgs boson at dim-5
- Not all DOFs are independent:
  - n_g DOFs can be removed via L_i → $$\frac{\partial_\mu a}{f_a}J^\mu_{L_i} = \frac{\partial_\mu a}{f_a}\left(\bar{L}^i_L\gamma^\mu L^i_L + \bar{e}^i_R\gamma^\mu e^i_R\right) = \frac{1}{32\pi^2}\frac{a}{f_a}\left(g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu} - g^2 W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu}\right)$$
  - 1 DOF can be removed via B → $$\frac{\partial_\mu a}{f_a}J^\mu_B = \frac{\partial_\mu a}{f_a}\sum_i \frac{\bar{Q}^i_L\gamma^\mu Q^i_L + \bar{u}^i_R\gamma^\mu u^i_R + \bar{d}^i_R\gamma^\mu d^i_R}{3} = \frac{n_g}{32\pi^2}\frac{a}{f_a}\left(g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu} - g^2 W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu}\right)$$

ALP effective field theory

- dimension-5 **linear effective Lagrangian**:

$$\mathscr{L}_{ALP} = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - c_{\tilde{B}}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{\tilde{W}}\frac{a}{f_a}W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu} - c_{\tilde{G}}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{\partial_\mu a}{f_a}\sum_{\substack{f=Q_L,\,L_L\\ u_R,\,d_R,\,e_R}} \bar{f}\gamma^\mu \mathbf{c}_f f$$

EWSB

- Couplings to **physical gauge bosons**:

$$-\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}g_{a\gamma Z}aF_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$-\frac{1}{4}g_{aZZ}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{1}{2}g_{aWW}aW^+_{\mu\nu}\tilde{W}^{-\mu\nu}$$

with

$$g_{a\gamma\gamma} = \frac{4}{f_a}(s^2_\theta c_{\widetilde{W}} + c^2_\theta c_{\widetilde{B}}) \qquad g_{a\gamma Z} = \frac{4}{f_a}s_{2\theta}(c_{\widetilde{W}} - c_{\widetilde{B}})$$

$$g_{aZZ} = \frac{4}{f_a}(c^2_\theta c_{\widetilde{W}} + s^2_\theta c_{\widetilde{B}}) \qquad g_{aWW} = \frac{4}{f_a}c_{\widetilde{W}}$$

G. Alonso-Álvarez, M.B. Gavela and P. Quilez [1811.05466]

$$g_{aWW} = g_{a\gamma\gamma} + \frac{c_w}{2s_w}g_{a\gamma Z}$$

$$g_{aZZ} = g_{a\gamma\gamma} + \frac{c^2_w - s^2_w}{2c_w s_w}g_{a\gamma Z}$$

One-loop corrections to ALPs couplings

- Some loop correctiones already computed in the literature:

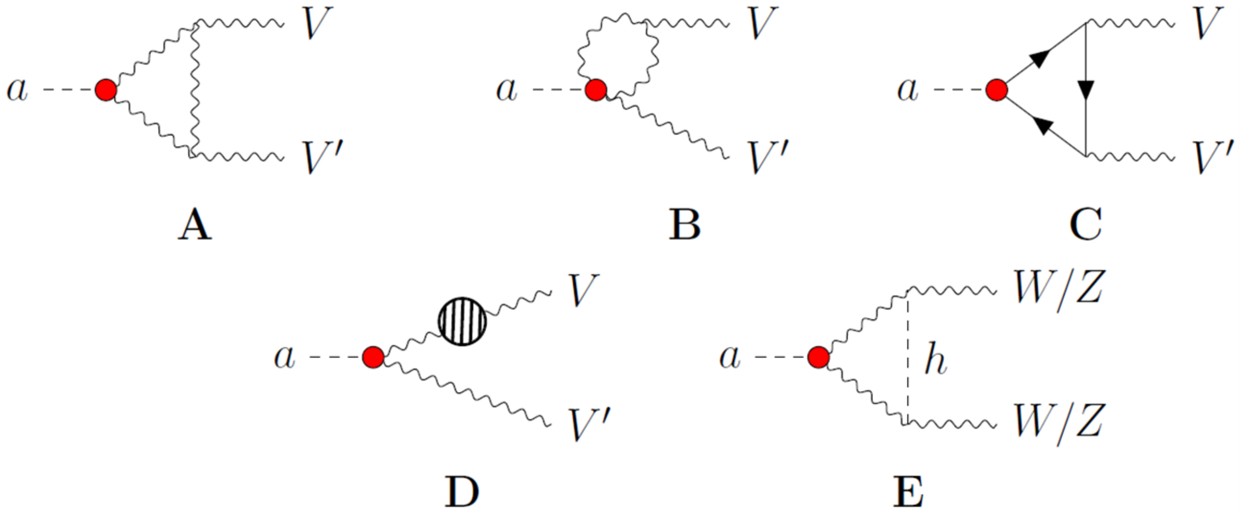
Corrections to $g_{a\gamma\gamma}$ + diagram ferm-A for light leptons → M. Bauer *et al.* [1708.00443]

Corrections to $g_{a\gamma Z}$ from diagram C → M. Bauer *et al.* [2012.12272]

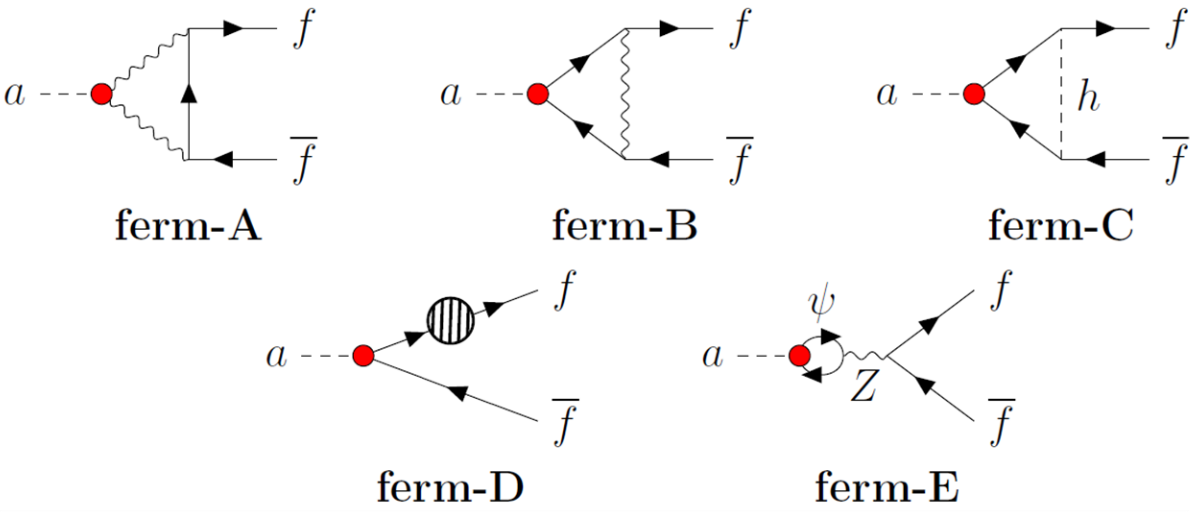
Renormalization group equations → M. Chala *et al.* [2012.09017]

J.B., I. Brivio, M.B. Gavela and V. Sanz [2107.11392]:

- Diagrams correcting $g_{a\gamma\gamma}$, g_{agg}, $g_{a\gamma Z}$, g_{aZZ} and g_{aWW}



- Diagrams correcting $\boldsymbol{c_{\mathrm{f}}}$ (flavor diagonal final state)



plus diagrams with would-be Goldstone bosons. All diagrams evaluated in a general $\boldsymbol{R_\xi}$ **gauge**.

→ This is the **first time** this computation is done → Including **all finite terms** → For **off-shell ALPs**

Results: tracking ALP-top coupling

- 1-loop top-quark-induced ALPs-electron interaction:

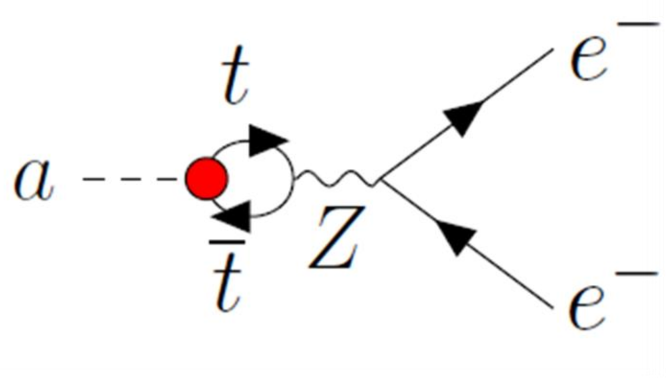
$$\mathbf{c_e^{eff}} = c_e + \frac{3\alpha_{em} m_t^2}{8\pi^2 s_w^2 M_W^2}\mathbf{c_t}\left\{\log\left(\frac{\Lambda^2}{m_t^2}\right) + 2 - 2i\sqrt{1-\frac{4m_t^2}{p^2}}\, f\left(\frac{4m_t^2}{p^2}\right)\right\}$$

Strongly constrained ($\mathbf{c_e^{eff}}$)

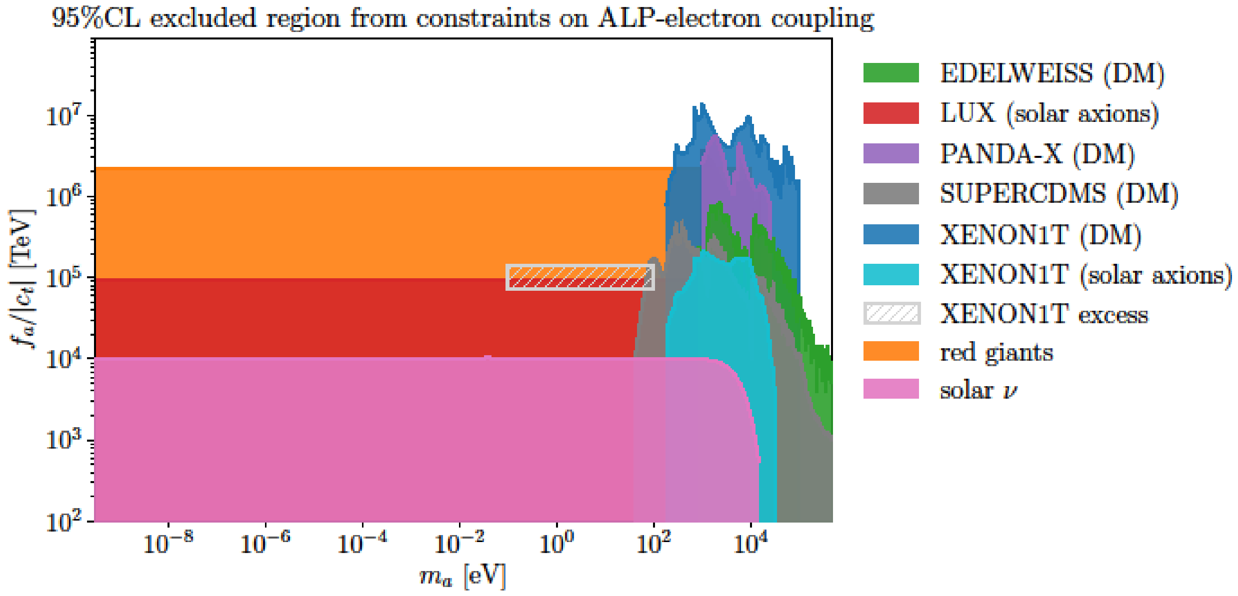
Weakly constrained ($\mathbf{c_t}$)

Full results at: https://notebookarchive.org/one-loop-corrections-to-alps-effective-couplings--2021-07-9otlr9o/

with $$f(\tau) = \begin{cases} \arcsin\frac{1}{\sqrt{\tau}} & \text{for } \tau \geq 1 \\ \frac{\pi}{2} + \frac{i}{2}\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} & \text{for } \tau < 1 \end{cases}$$



- Relevant for electron recoil experiments (i.e. XENON)
- Bounds for **light ALPs**



Results: tracking ALP-top coupling

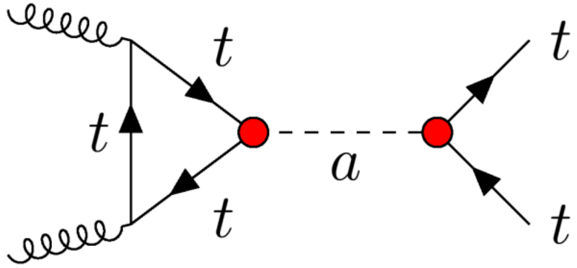
- 1-loop top-quark-induced $gg \to a \to t\bar{t}$:

$$g_{agg}^{\text{eff}} = g_{agg} - \frac{\alpha_s}{2\pi f_a} \mathbf{c_t} \left\{ 1 - \frac{4m_t^2}{p^2} f^2\left(\frac{4m_t^2}{p^2}\right)\right\}$$

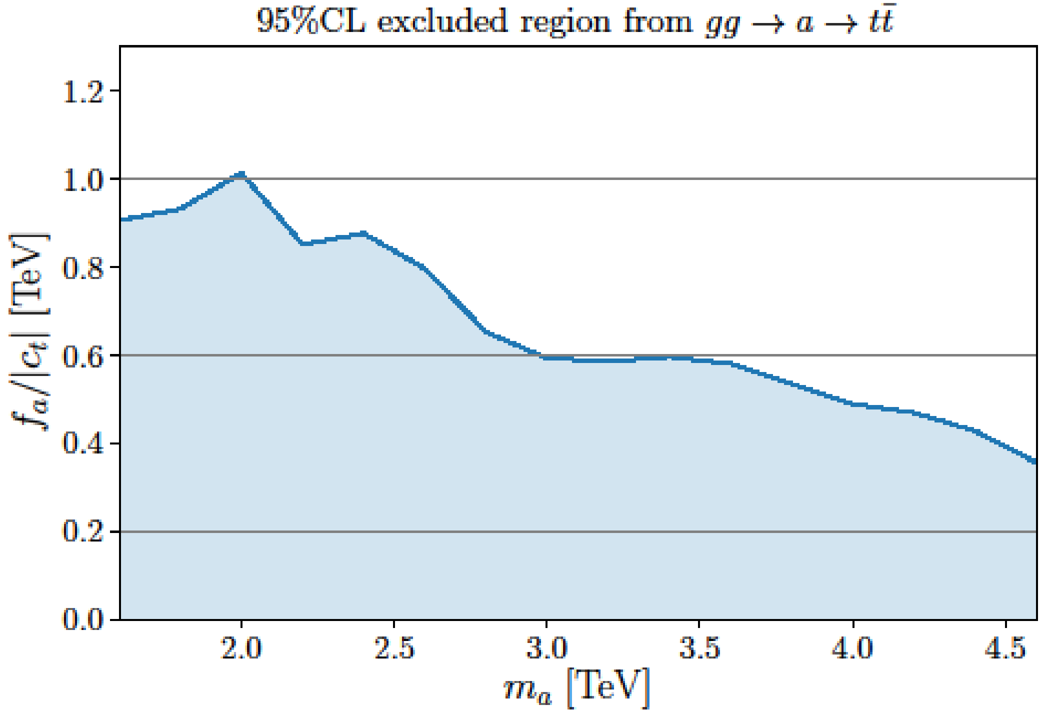
Strongly constrained

Weakly constrained

with $f(\tau) = \begin{cases} \arcsin \frac{1}{\sqrt{\tau}} & \text{for } \tau \geq 1 \\ \frac{\pi}{2} + \frac{i}{2} \ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} & \text{for } \tau < 1 \end{cases}$



- Relevant for collider and LHC searches
- Bounds for **heavy ALPs**



data from ATLAS search for $t\bar{t}$ resonances at LHC [2005.05138]

Gauge invariance relations @ 1 loop

$$g_{aWW} = g_{a\gamma\gamma} + \frac{c_w}{2s_w} g_{a\gamma Z}$$
$$g_{aZZ} = g_{a\gamma\gamma} + \frac{c_w^2 - s_w^2}{2c_w s_w} g_{a\gamma Z}$$

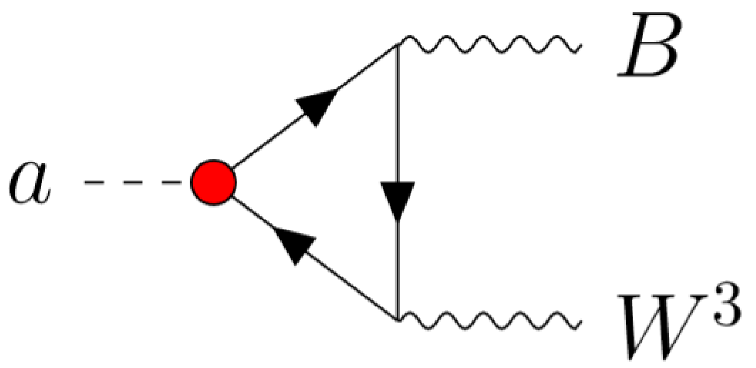
Loop corrections →

$$g_{aWW} = g_{a\gamma\gamma} + \frac{c_w}{2s_w} g_{a\gamma Z} - \frac{c_w}{2s_w}\Delta_{BW} - \Delta_{WW}$$
$$g_{aZZ} = g_{a\gamma\gamma} + \frac{c_w^2 - s_w^2}{2c_w s_w} g_{a\gamma Z} - \frac{1}{2c_w s_w}\Delta_{BW}$$

where: $\mathscr{L} \supset -\frac{1}{4}\Delta_{BW}\, aB_{\mu\nu}\tilde{W}^{3\,\mu\nu} - \frac{1}{4}\Delta_{WW}\, aW^3_{\mu\nu}\tilde{W}^{3\,\mu\nu}$ gauge-breaking operators? What is their origin?

- Proportional to gauge-breaking parameters in SM (higgs vev):

$$\Delta_{BW},\, \Delta_{WW} \propto m_t^2$$
$$\Delta_{BW},\, \Delta_{WW} \to 0 \text{ for } v \to 0$$



- **Gauge invariant formulation**: corrections to higher dimensional operators:

$$a(\Phi^\dagger\Phi)^n(\Phi^\dagger\sigma^i\Phi)B_{\mu\nu}W^{i\,\mu\nu} \to \Delta_{BW}$$
$$a(\Phi^\dagger\Phi)^n(\Phi^\dagger\sigma^i\Phi)(\Phi^\dagger\sigma^j\Phi)W^i_{\mu\nu}W^{j\,\mu\nu} \to \Delta_{WW}$$

ALP collider searches

- **Stable ALP searches**:
  - Mono-W, Z and γ — K. Mimasu, V. Sanz [1409.4792], ATLAS [2011.05259], I. Brivio, M.B. Gavela, L. Merlo, K. Mimasu, J.M. No, R. del Rey, V. Sanz [1701.05379]
  - Mono-jet and di-jet — K. Mimasu, V. Sanz [1409.4792], G. Haghighat, D.H. Raissi, M.M. Najafabadi [2006.05302], ATLAS [2102.10874], F.A. Ghebretinsae , K. Wang, Z.S. Wang [2203.01734]
  - $pp \to W\gamma a$, $pp \to t\bar{t}a$ — I. Brivio, M.B. Gavela, L. Merlo, K. Mimasu, J.M. No, R. del Rey, V. Sanz [1701.05379], M. Bauer, (M. Heiles), M. Neubert, A. Thamm [1708.00443], [1808.10323]
- **Resonant searches**:
  - $pp \to \gamma\gamma$ resonant production — J. Jäckel, M. Jankowiak, M. Spannowsky [1212.3620], (Cid Vidal), A.Mariotti, D. Redigolo, F. Sala, K. Tobioka [1710.01743], [1810.09452], M. Bauer, M. Heiles, M. Neubert, A. Thamm [1808.10323]
  - $\gamma\gamma \to \gamma\gamma$ in Pb-Pb collisions — S. Knapen, T. Lin, H.K. Lou, T. Melia [1607.06083], [1709.07110], C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon [1803.10835], CMS [1810.04602], ATLAS [2008.05355]
  - $pp \to V_1 a \to V_1 V_2 V_3$ tri-boson production — J. Jäckel, M. Spannowsky [1509.00476], N. Craig, A. Hook, S. Kasko [1805.06538], (J. Ren), D. Wang, L. Wu, J.M. Yang, M. Zhang [2102.01532], [2106.07018]

New idea: nonresonant ALP-mediated diboson production

- Original idea: M. B. Gavela, J. M. No, V. Sanz, and J. F. de Troconiz, [1905.12953]

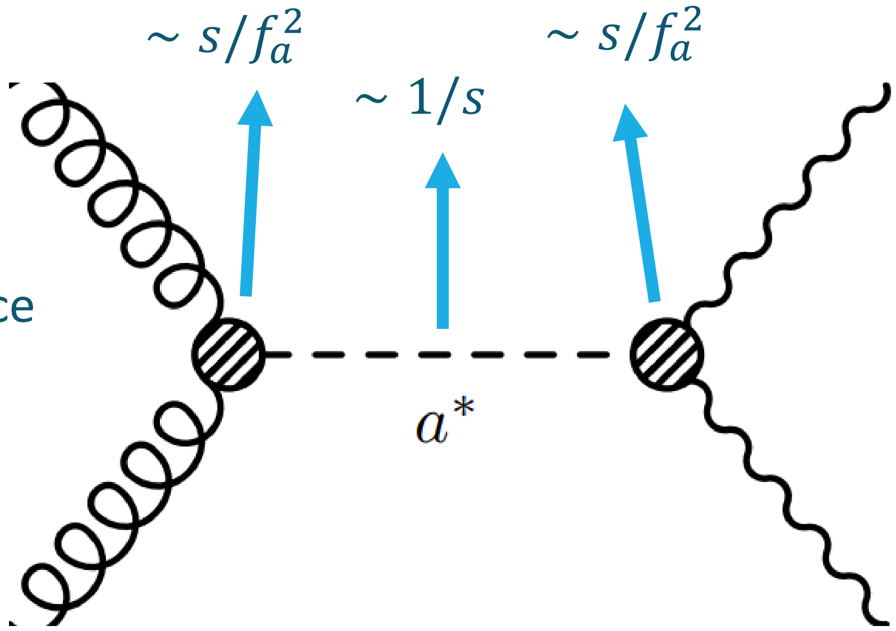
- Very off-Shell ALP mediates the process:
$$m_a \ll \sqrt{s}$$

- Cross sections **independent of the ALP mass** m_a and decay width Γ_a: allow to explore large areas in the parameter space

- Suppression from $\sqrt{s}$ is compensated by the derivative nature of ALP couplings:
$$\hat{\sigma} \propto s/f_a^4$$

- Constraints on the product $g_{agg} \times g_{aVV}$

- Gluon fusion initiated (ggF)

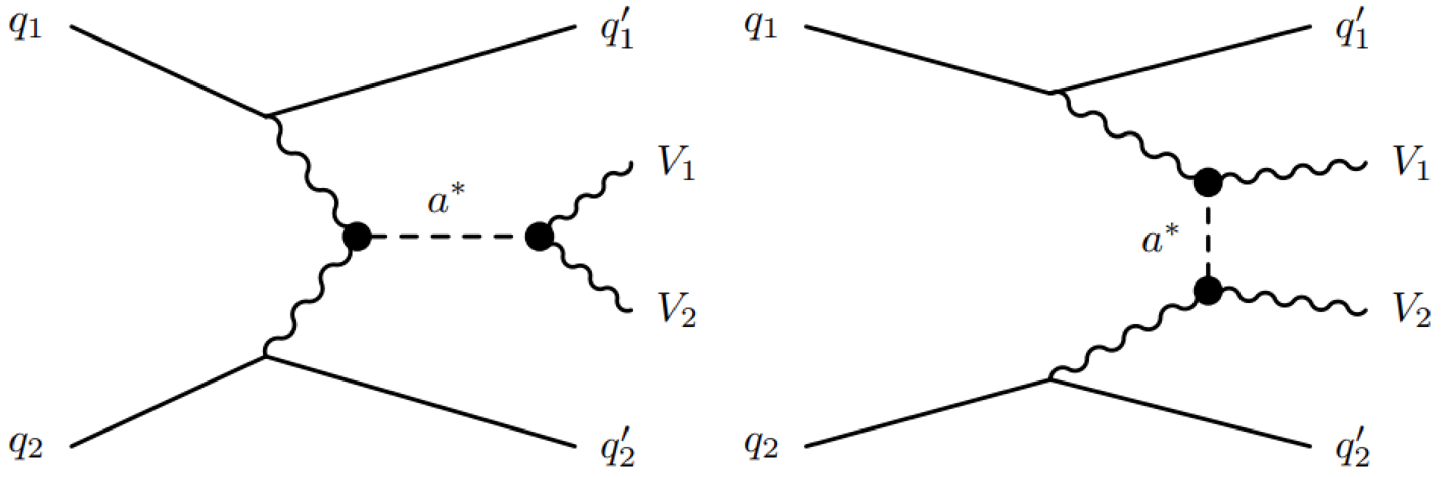


M. B. Gavela, J. M. No, V. Sanz, and J. F. de Troconiz, [1905.12953]
see also: S. Carrá, *et al.* [2106.10085] and CMS-B2G-20-013

ALP-mediated EW VBS

- This work: **Vector Boson Scattering**
  → production of a diboson pair + 2 face-to-face jets with high invariant mass
  → explore **ALP EW couplings** with reduced dependence on the gluon coupling

- EW ALP-mediated processes $q_1 q_2 \to q_1' q_2' V_1 V_2$



VBS s-channel VBS t-channel

- In this work: reinterpretation of Run 2 CMS analysis:
$V_1 V_2 = ZZ, Z\gamma, W^{\pm}\gamma, W^{\pm}Z, W^{\pm}W^{\pm}$

CMS-SMP-20-001, CMS-SMP-20-016, CMS-SMP-19-008, CMS-SMP-19-012

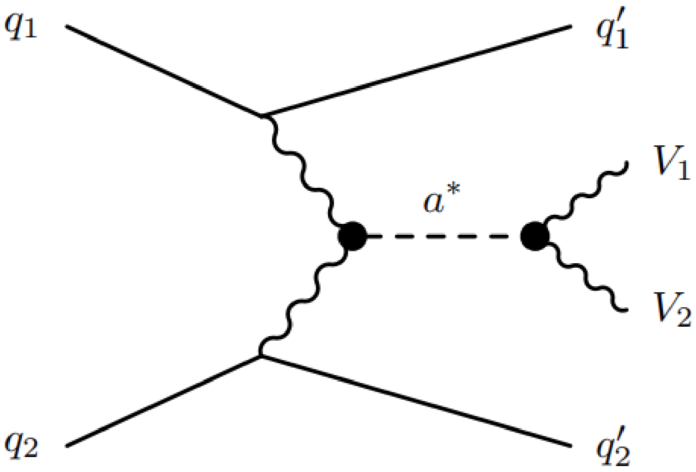
JB, I. Brivio, J. Machado-Rodríguez and J. F. de Trocóniz [2202.0345]

ALP-mediated EW VBS

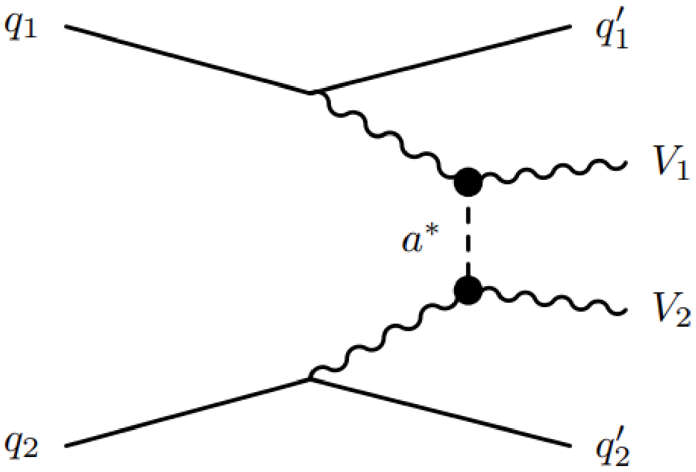
$$\sigma_{ALP} = \sigma_{SM} + \frac{1}{f_a^2}\sigma_{\text{interf.}} + \frac{1}{f_a^4}\sigma_{\text{signal}}$$

$$\sigma_{\text{interf.}} = c_{\widetilde{B}}^{2}\sigma_{B2} + c_{\widetilde{W}}^{2}\sigma_{W2} + c_{\widetilde{B}}c_{\widetilde{W}}\sigma_{BW}$$

$$\sigma_{\text{signal}} = c_{\widetilde{B}}^{4}\sigma_{B4} + c_{\widetilde{W}}^{4}\sigma_{W4} + c_{\widetilde{B}}^{2}c_{\widetilde{W}}^{2}\sigma_{B2W2} + c_{\widetilde{B}}^{3}c_{\widetilde{W}}\sigma_{B3W} + c_{\widetilde{B}}c_{\widetilde{W}}^{3}\sigma_{BW3}$$



VBS s-channel



VBS t-channel

- In this work: reinterpretation of Run 2 CMS analysis:

$V_1V_2 = ZZ, Z\gamma, W^{\pm}\gamma, W^{\pm}Z, W^{\pm}W^{\pm}$

CMS-SMP-20-001, CMS-SMP-20-016, CMS-SMP-19-008, CMS-SMP-19-012

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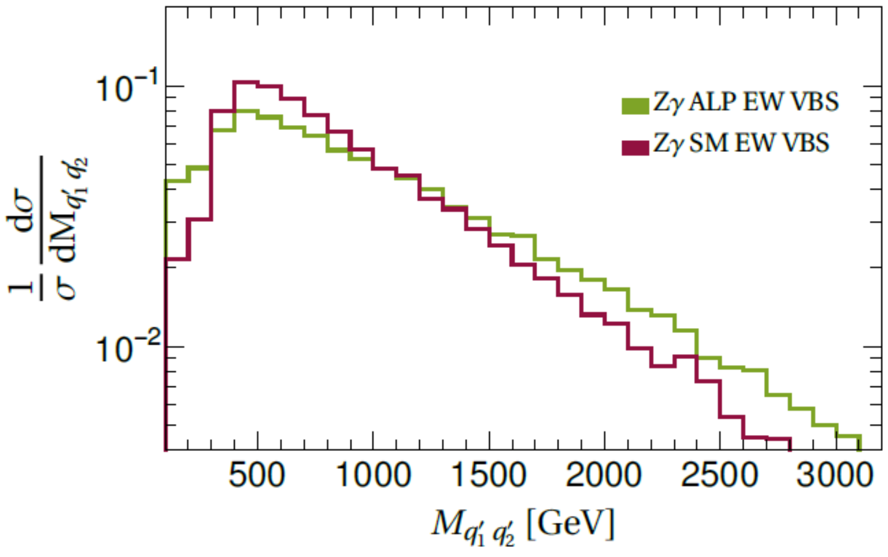
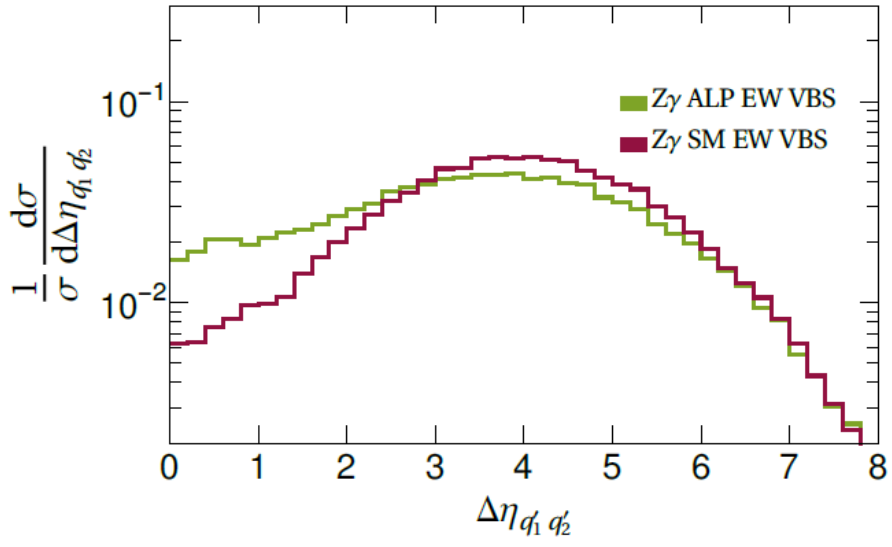
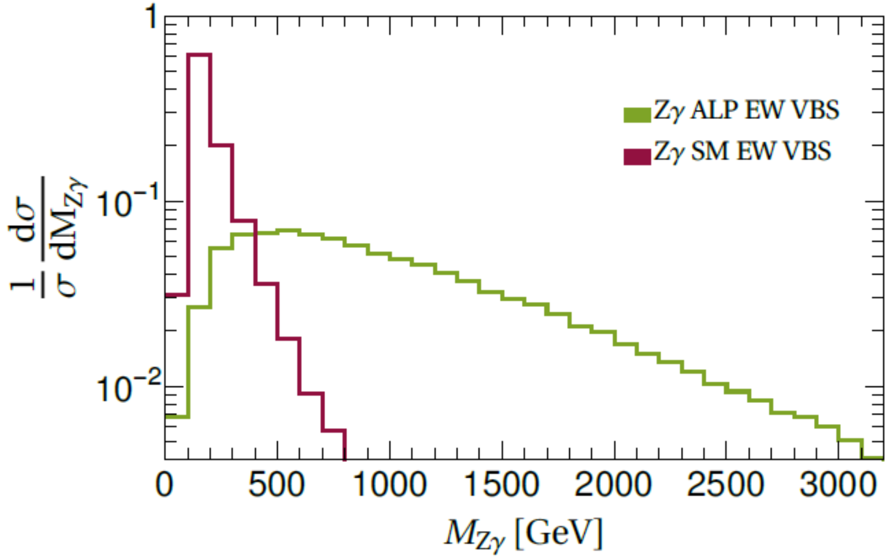
ALP-mediated EW VBS



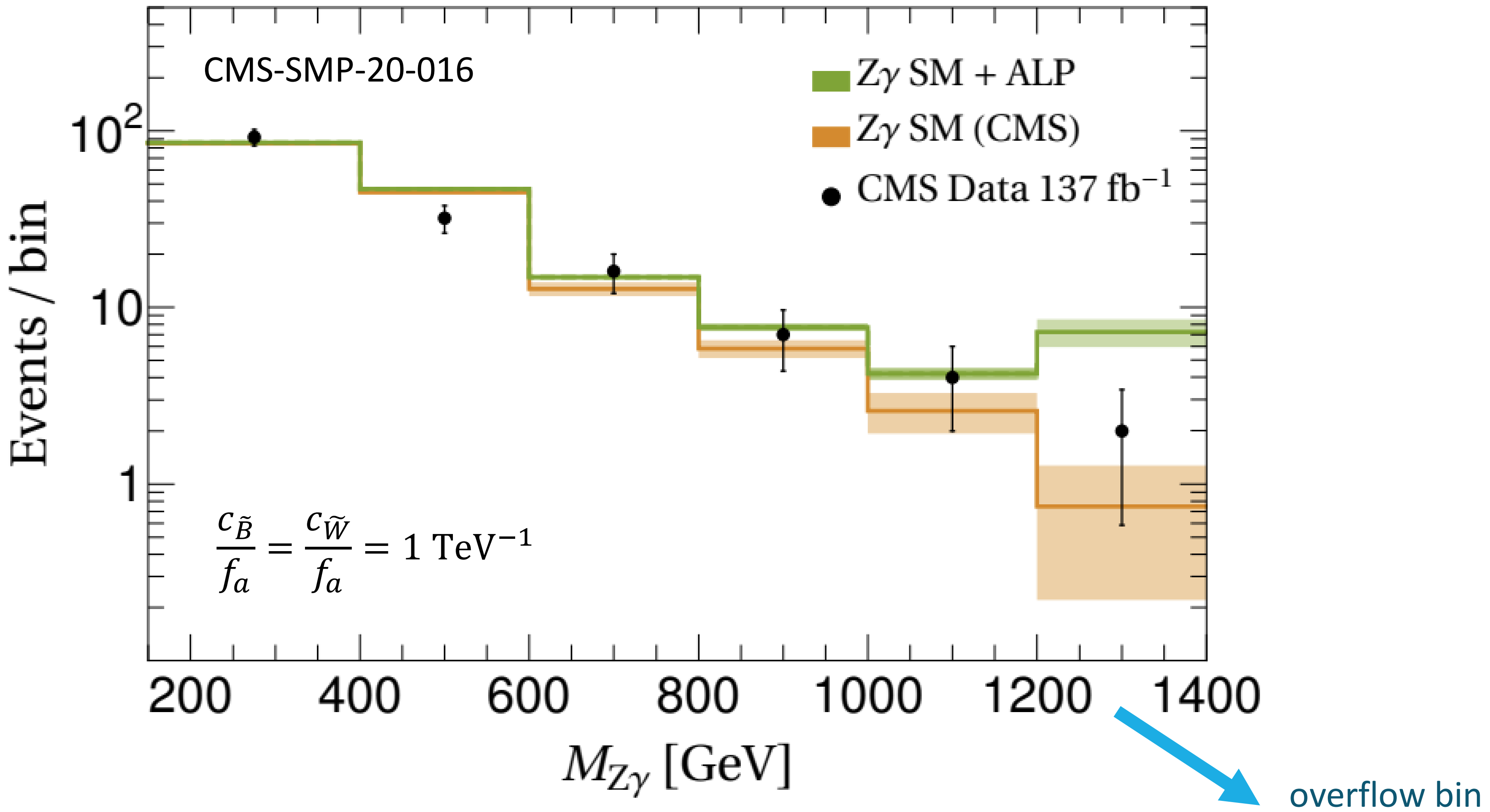


$$\frac{c_{\tilde{B}}}{f_a} = \frac{c_{\widetilde{W}}}{f_a} = 1\ \mathrm{TeV}^{-1}$$

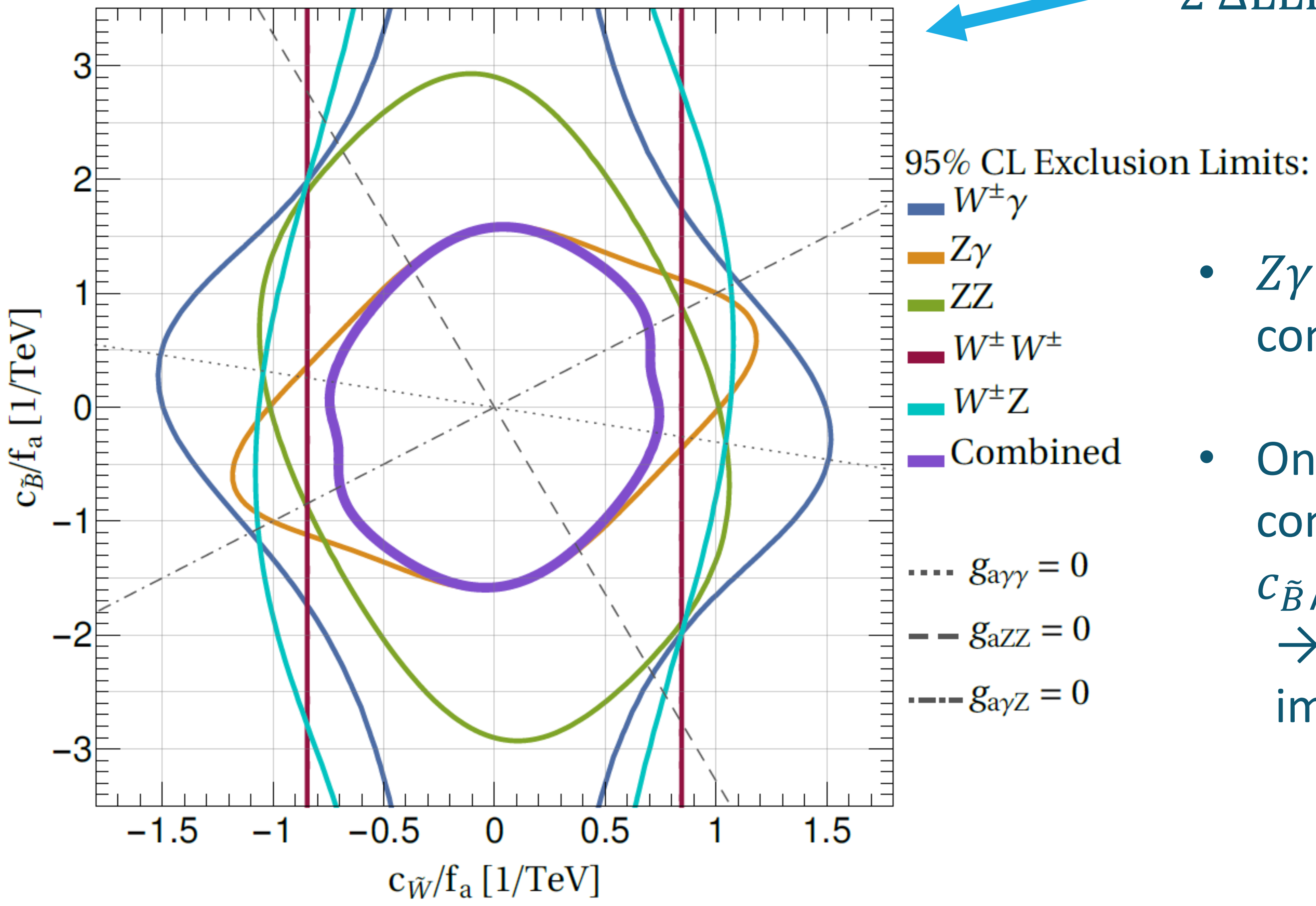


ALP-mediated processes tend to have larger values of $M_{V_1 V_2}$

ALP-mediated EW VBS



Results

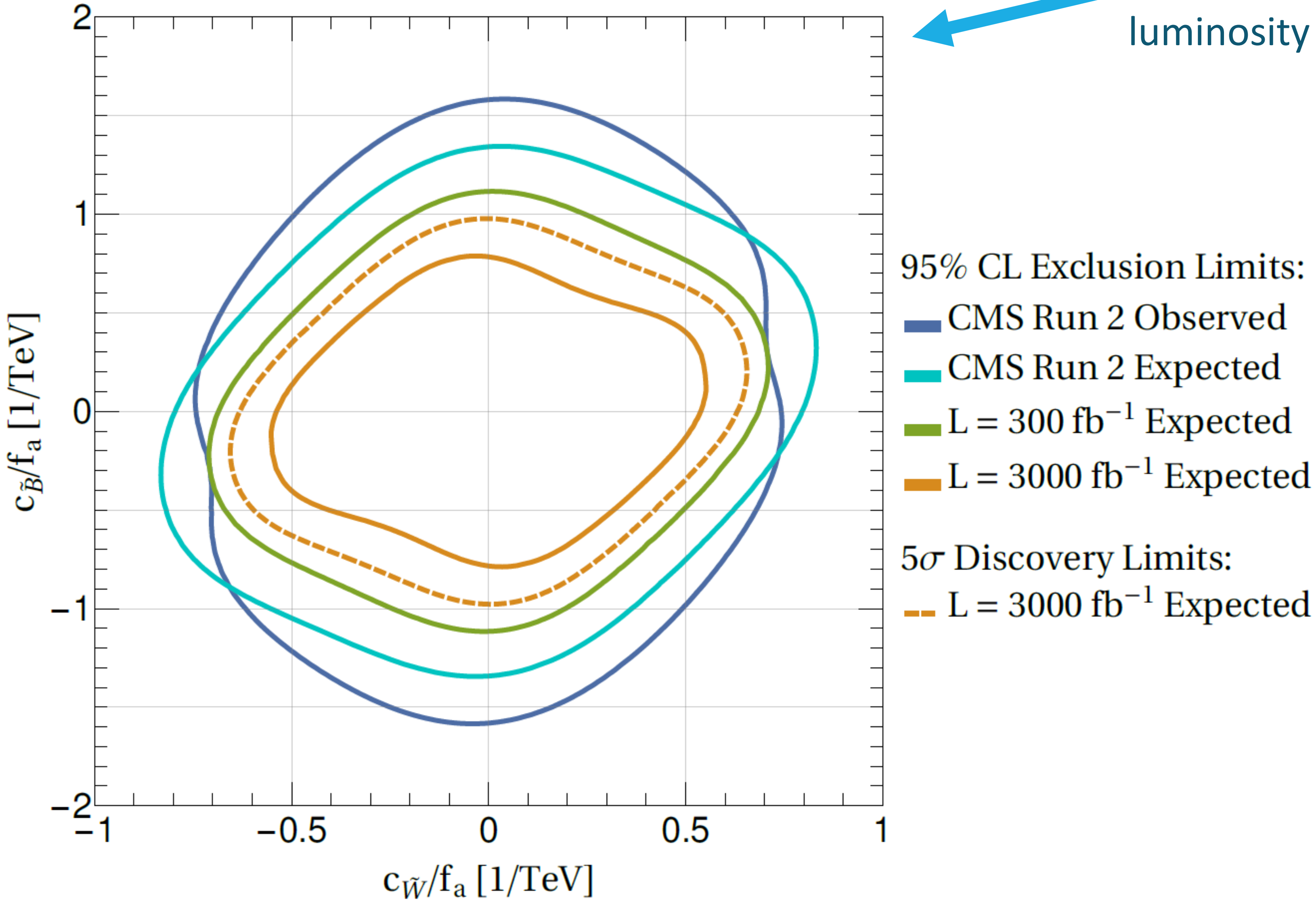


$-2\,\Delta\text{LLR} = 3.84$

- $Z\gamma$ and $W^{\pm}W^{\pm}$ are the most constraining channels

- Only $Z\gamma$ and ZZ can constraint the plane in the $c_{\tilde{B}}/f_a$ direction.
  → high-mass $\gamma\gamma$ channel can improve it

Projections

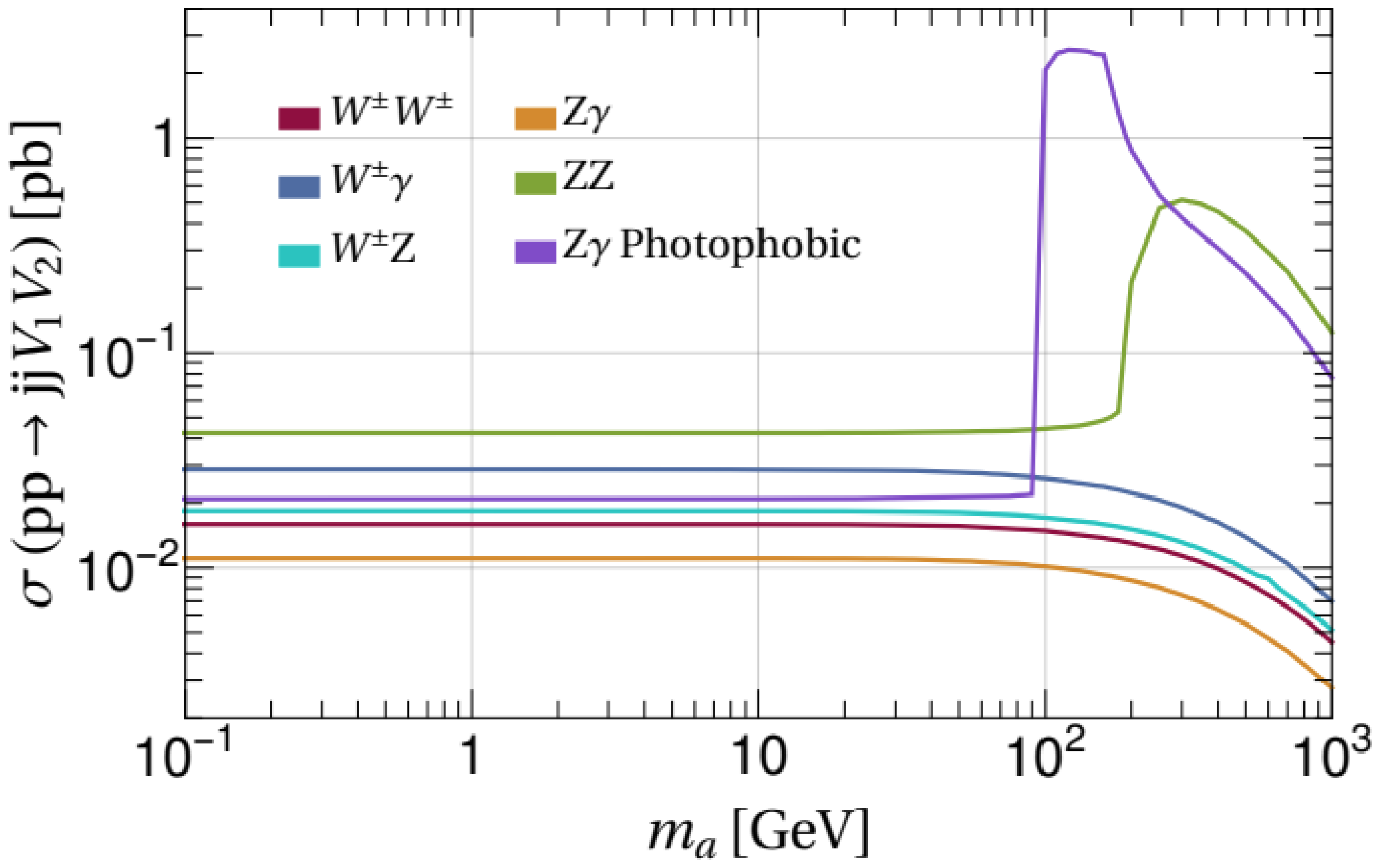


Simple rescaling in luminosity and $\sqrt{\hat{s}} \to 14$ TeV

HL-LHC:

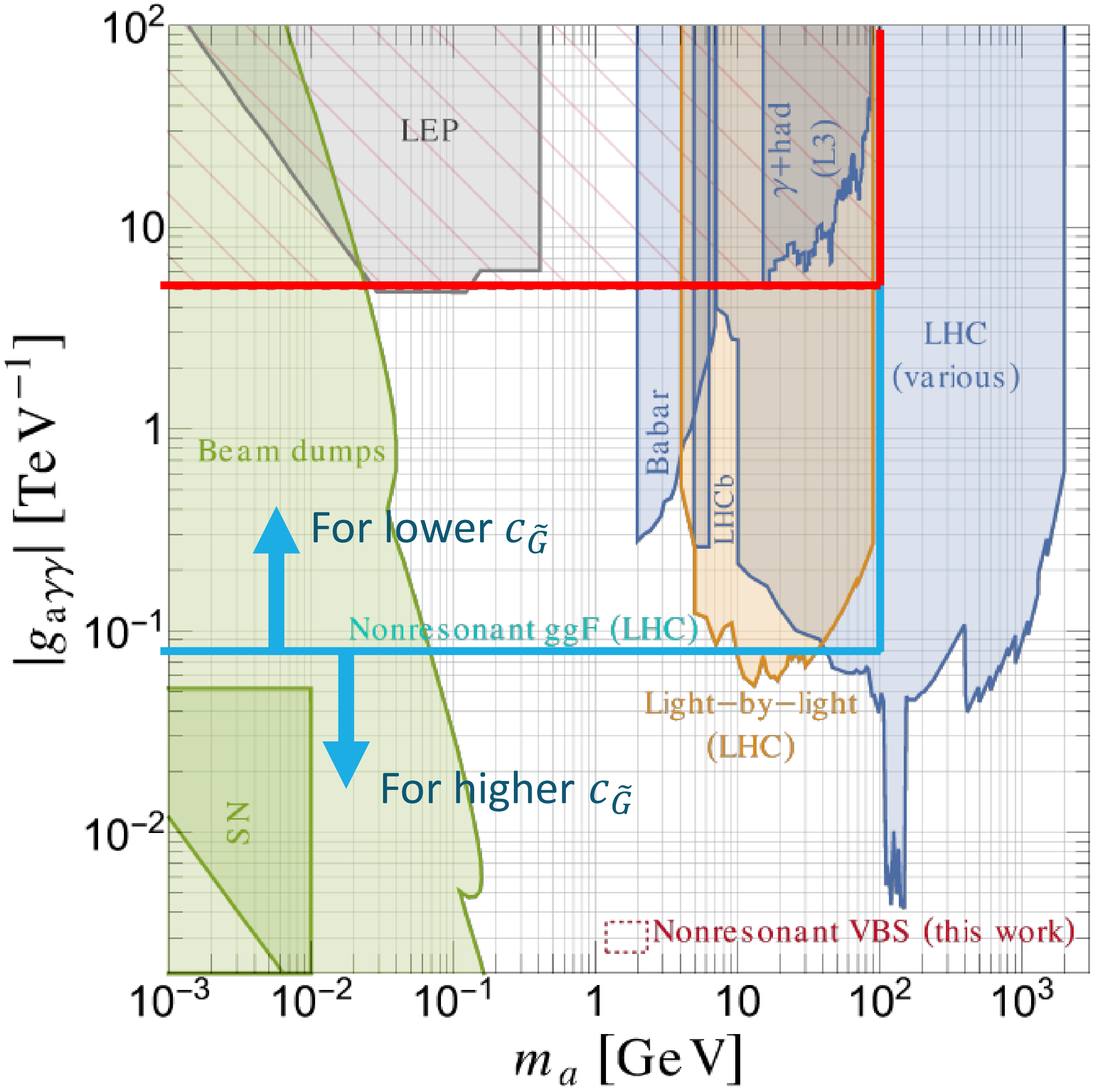
- Limits on the couplings decrease by a factor $1.5 - 1.7$
- Limits on the cross sections decrease by a factor $5 - 8$

Dependence on the ALP mass



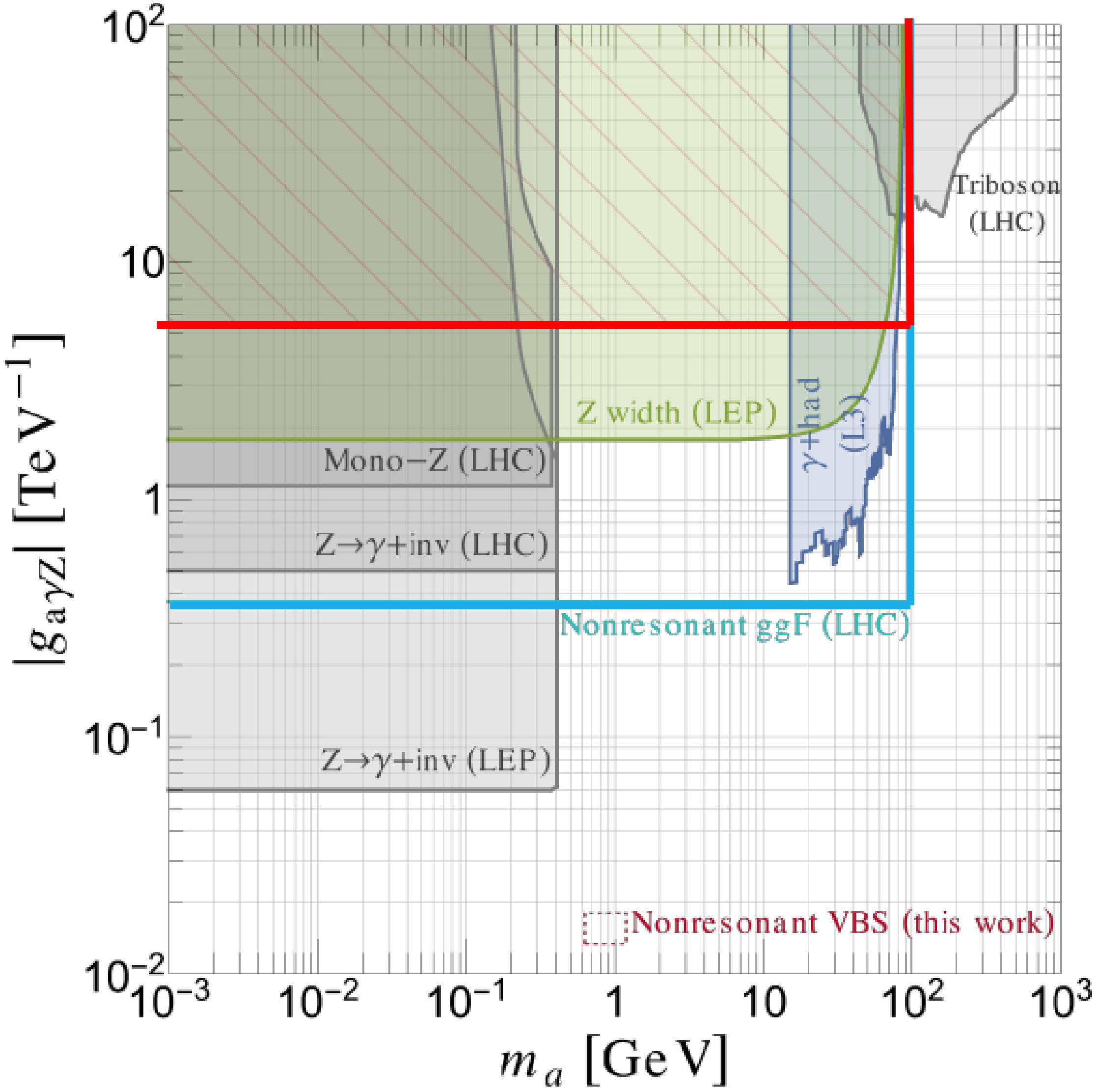
- Up to masses of 100 GeV the variations in the cross sections are $< 10\%$
- Exception: $Z\gamma$ channel, but the resonant peak is not visible in the histogram (first bin starts at $\sim$ 160 GeV)

Comparison with existing bounds

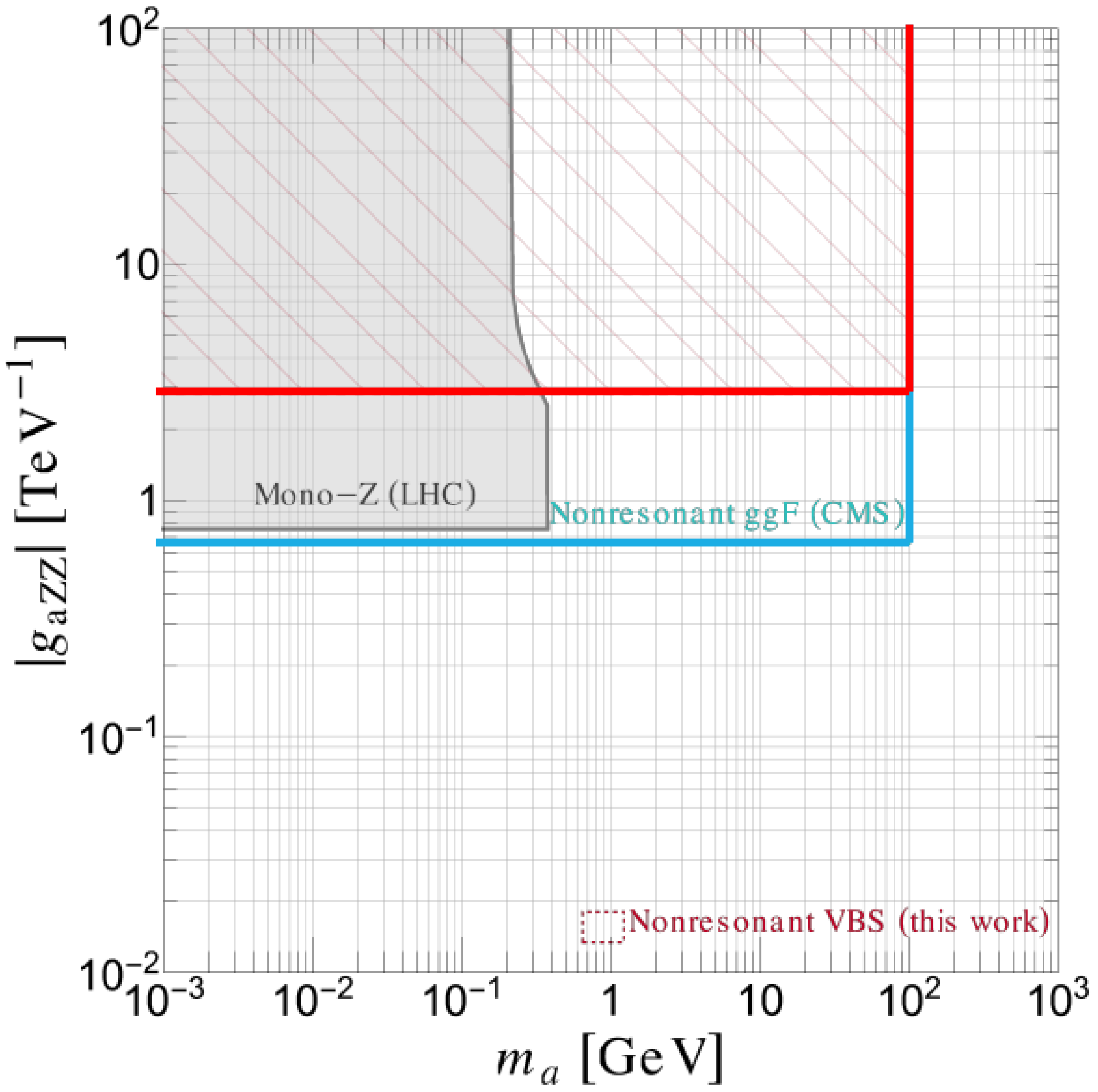


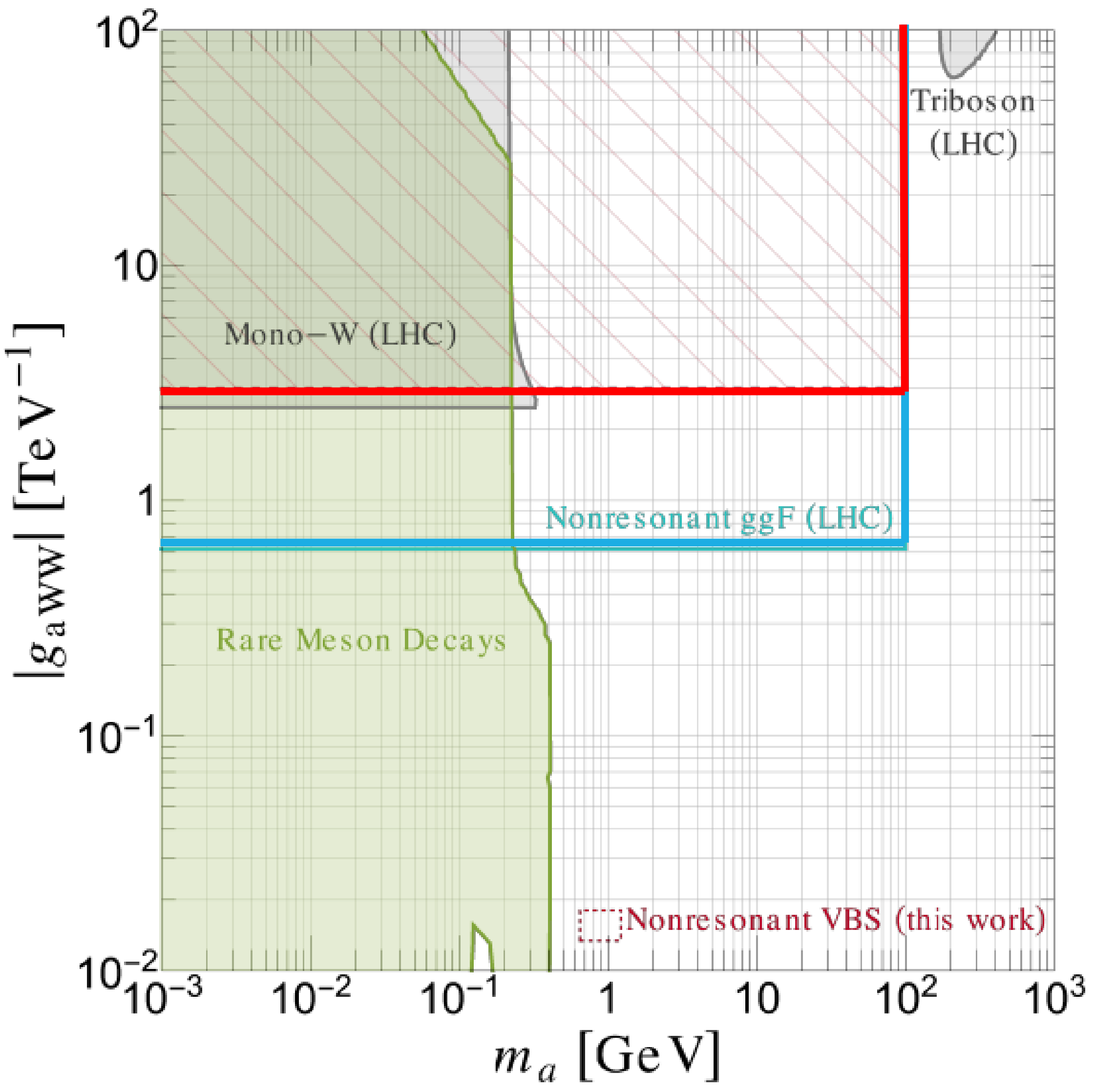
- Red: this work
- Green: no assumptions
- Light blue: nonresonant ggF. Depend on the coupling to gluons and assume $g_{agg} = 1\ \mathrm{TeV}^{-1}$
- Dark blue: gluon dominance: $g_{agg} \gg g_{aV_1V_2}$
- Orange: light-by-light: $BR(a \to \gamma\gamma) = 1$
- Grey: more elaborate assumptions or assumptions on the EW sector itself

Comparison with existing bounds



Comparison with existing bounds





Conclusions

- **ALPs** are well-motivated from many BSM and good DM candidates
  → Rich phenomenology
  → Simple EFT with a limited number of parameters

- **Experimental precision** requires to look for **one-loop** corrections
  → Relevant for ALP experimental searches

- New idea: collider searches for **non-resonant ALP signals**
  → cross sections **independent of the mass** and decay width of the ALP
  → large areas in the ALP parameter space are explored

- **VBS channels** allow measurements of **EW ALP couplings** with reduced dependence on the ALP-gluon $c_{\tilde{G}}$