# ALP signals in diboson and VBS

Ilaria Brivio

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mostly based on:

Bonilla, IB, Machado-Rodríguez, Trocóniz **2203.03450**
IB, Éboli, González-García **2106.05977**

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Swiss National
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# Axion-Like Particles

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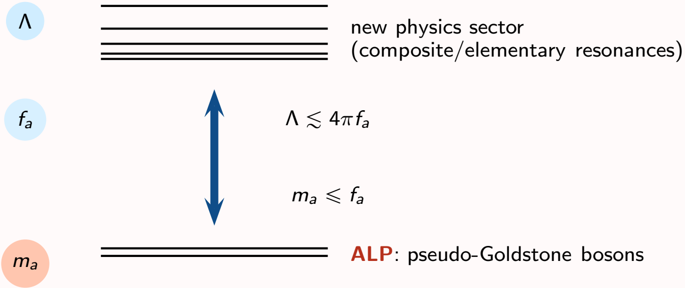
**ALP** = pseudo-Goldstone boson from breaking of BSM symmetry

Examples:

| | | | |
|---|---|---|---|
| Peccei-Quinn symm. | → | QCD axion | Peccei,Quinn 1977, Weinberg 1978<br>Wilczek 1978 |
| Lepton number | → | Majoron | Gelmini,Roncadelli 1981<br>Langacker,Peccei,Yanagida 1986 |
| Flavor symm. | → | Flavon | Wilczek 1982 |



$\Lambda$ new physics sector (composite/elementary resonances)

$f_a$

$\Lambda \lesssim 4\pi f_a$

$m_a \leqslant f_a$

$m_a$ **ALP**: pseudo-Goldstone bosons

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## Fundamental properties

- neutral, pseudo-scalar: spin 0, odd parity
- approx. shift symmetry $a(x) \to a(x) + c$ $\Rightarrow m_a$ **naturally small**

## Why so interesting?

- naturally the lightest remnant of heavy NP sectors → easiest to discover
- spontaneous symmetry breakings are **ubiquitous** in BSM → high relevance
- under certain conditions: good **DM** candidate

# ALP Effective Field Theory

- ALPs can be described in a **EFT** where heavy sector is integrated out
- model-independent → many birds with one stone
- SM fields + $a$ & SM symmetries + ALP shift sym. (+ CP)
- Cutoff: $f_a$ (ALP char. scale, reminiscent of $f_\pi$). LO: dimension 5

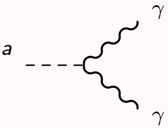
Georgi,Kaplan,Randall PLB169B(1986)73

$$\begin{aligned}\mathcal{L}_{ALP} &= \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 \\ &+ C_{\tilde{B}} O_{\tilde{B}} + C_{\tilde{W}} O_{\tilde{W}} + C_{\tilde{G}} O_{\tilde{G}} \\ &+ C_u O_u + C_d O_d + C_e O_e + C_Q O_Q + C_L O_L \quad + \mathcal{O}(f_a^{-2})\end{aligned}$$

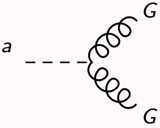
$$O_{\tilde{B}} = -\frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} \qquad O_{\tilde{W}} = -\frac{a}{f_a} W^I_{\mu\nu} \tilde{W}^{I\mu\nu} \qquad O_{\tilde{G}} = -\frac{a}{f_a} G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$

$$O_{f,ij} = \frac{\partial^\mu a}{f_a} \left(\bar{f}_i \gamma^\mu f_j\right)$$

# ALP couplings

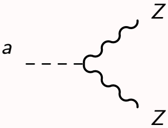


$$g_{a\gamma\gamma} \sim (s_\theta^2\, \boxed{C_{\tilde W}} + c_\theta^2\, \boxed{C_{\tilde B}})$$

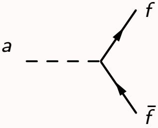


$$g_{aGG} \sim \boxed{C_{\tilde G}}$$

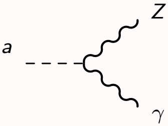
$$(+aG^3, aG^4)$$



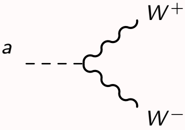
$$g_{aZZ} \sim (c_\theta^2\, \boxed{C_{\tilde W}} + s_\theta^2\, \boxed{C_{\tilde B}})$$



$$g_{aff} \sim \boxed{C_f}$$



$$g_{a\gamma Z} \sim s_{2\theta}(\boxed{C_{\tilde W}} - \boxed{C_{\tilde B}})$$



$$g_{aWW} \sim \boxed{C_{\tilde W}}$$

$$(+aWWZ, aWW\gamma)$$

coupling to Higgs only at

$$d = 6\ (\partial_\mu a \partial^\mu a)(H^\dagger H)$$

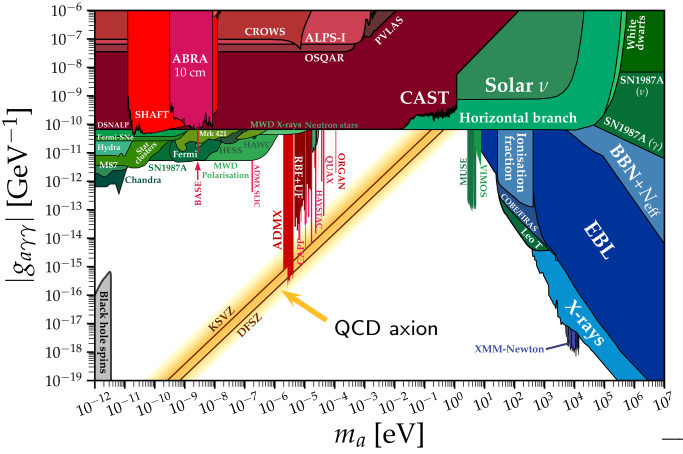
$$d = 7\ (\partial_\mu a)(H^\dagger i \overleftrightarrow{D^\mu} H)(H^\dagger H)$$

Bauer,Neubert,Thamm 1704.08207,1708.00443

# A vast phenomenology

allowed ranges for $m_a$ and $C_i/f_a$ span several orders of magnitude

→ trade-off for model-independence



© cajohare.github.io/AxionLimits/

⟶
extends even further (>GeV)

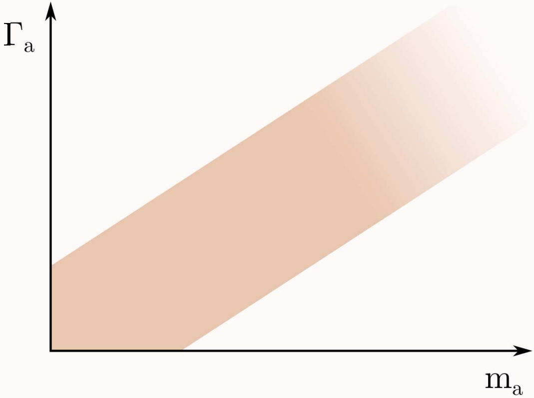
# ALPs @ LHC

# ALPs at the LHC

### Why?

- tree-level access to **couplings to heavy SM particles** $(W, Z, h, t)$
- access to **heavy ALPs** $(m_a \gtrsim 10s\ \text{GeV})$

### How?



# ALPs at the LHC

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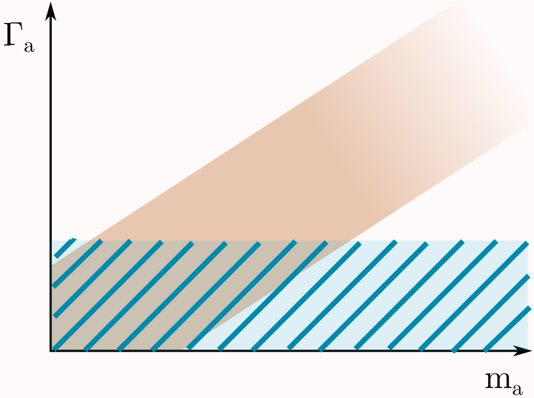
**How?**

**stable ALP**

$\downarrow$

$\not{E}_T$



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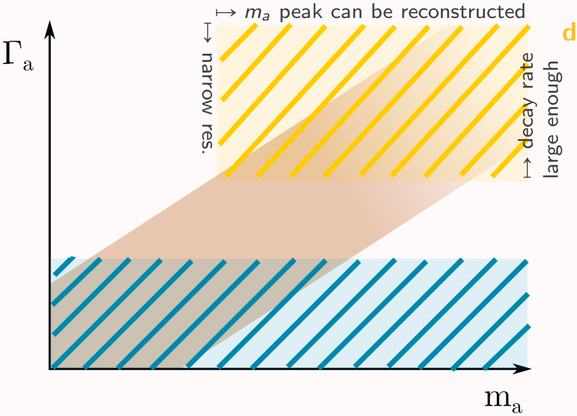

**massive, decaying ALP**

↓

resonant

**stable ALP**

↓

$\not{E}_T$

# ALPs at the LHC

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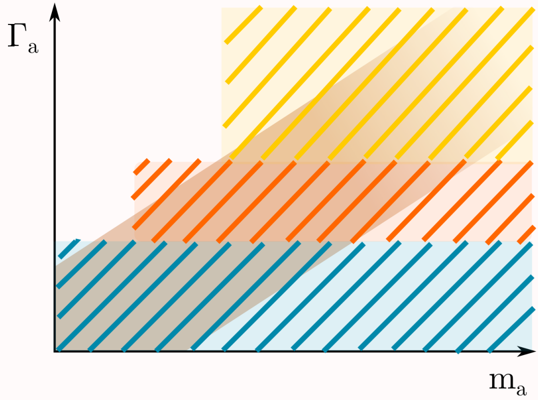

**massive, decaying ALP**
↓
resonant

**long-lived ALP**
↓
displaced vertices

**stable ALP**
↓
$\cancel{E}_T$

# ALPs at the LHC

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- tree-level access to **couplings to heavy SM particles** $(W, Z, h, t)$
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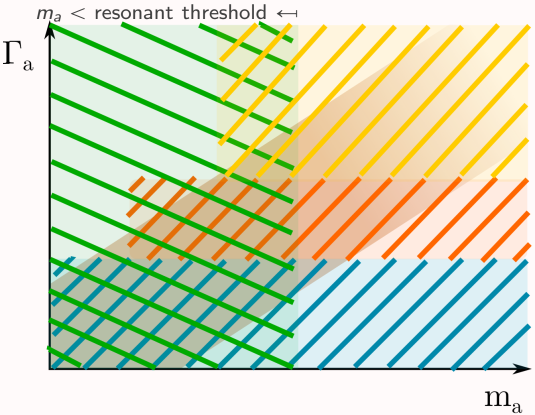


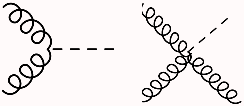
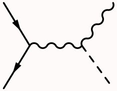
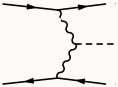
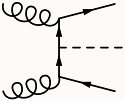
**off-shell ALP**
↓
non-resonant

**stable ALP**
↓
$\not{E}_T$

**massive, decaying ALP**
↓
resonant

**long-lived ALP**
↓
displaced vertices

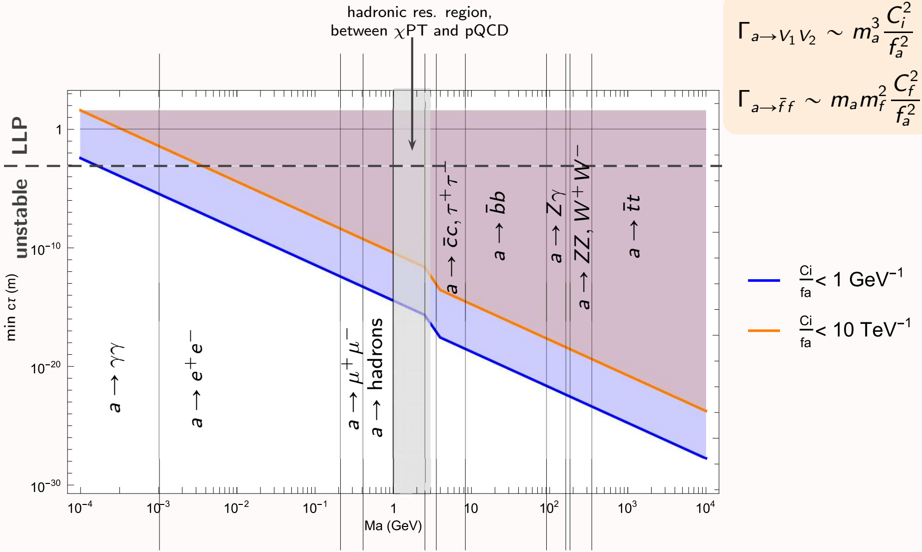
# ALP at LHC: main production modes

- $Z \to a\gamma$ $C_{\tilde{B}}$ $C_{\tilde{W}}$
- 
  $gg \to a(g)$ $C_{\tilde{G}}$
- 
  $q\bar{q} \to Va,\ V = Z, W^{\pm}, \gamma$ $C_{\tilde{B}}$ $C_{\tilde{W}}$
- 
  $q\bar{q} \to q\bar{q}a$ $C_{\tilde{B}}$ $C_{\tilde{W}}$ $C_{\tilde{G}}$ (also: light-by-light in Pb collisions)
- 
  $gg \to \bar{t}ta$ $C_f$

# ALP decay modes and lifetime

$$\Gamma_{a\to V_1 V_2} \sim m_a^3 \frac{C_i^2}{f_a^2}$$

$$\Gamma_{a\to \bar{f} f} \sim m_a m_f^2 \frac{C_f^2}{f_a^2}$$



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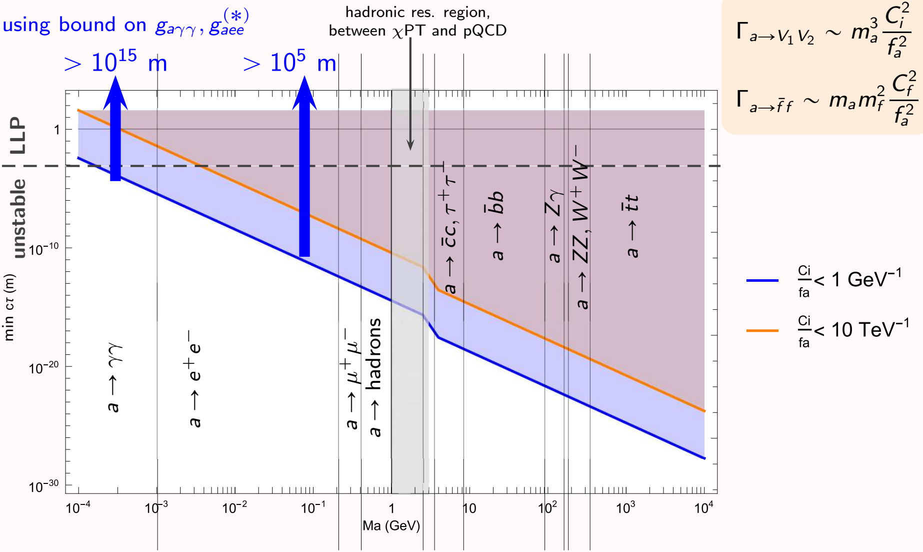

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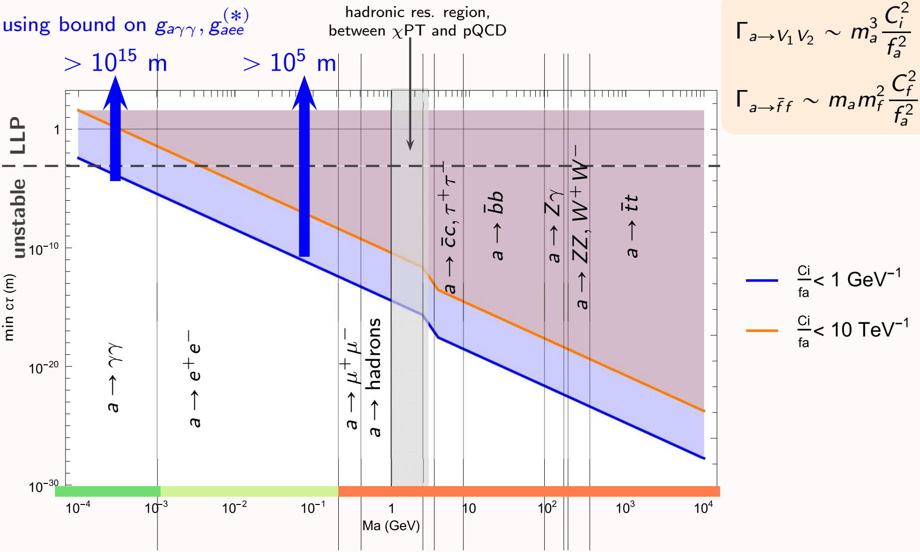

$m_a \lesssim 1\,\mathrm{MeV}$ stable

$m_a > 200\,\mathrm{MeV}$ assuming stability restrict space
(larger $m_a \to$ smaller $C_i/f_a$)

# ALP decay modes and lifetime

$$\Gamma_{a\to V_1 V_2} \sim m_a^3 \frac{C_i^2}{f_a^2}$$

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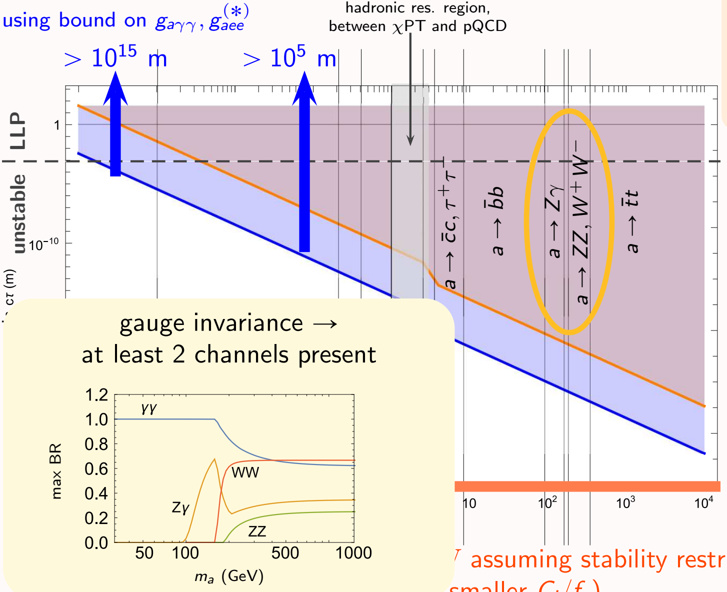


using bound on $g_{a\gamma\gamma}, g_{aee}^{(*)}$

$> 10^{15}$ m

$> 10^{5}$ m

hadronic res. region,
between $\chi$PT and pQCD

gauge invariance →
at least 2 channels present

assuming stability restrict space
(larger $m_a$ smaller $C_i/f_a$)

# ALPs signals at LHC: explored so far

incomplete list! omitting Higgs & flavor viol.

## Stable

- mono-Z, mono-W, mono-$\gamma$ Mimasu,Sanz 1409.4792, ATLAS 2011.05259 IB,Gavela,Merlo,Mimasu,No,delRey,Sanz 1701.05379
- mono-jet, di-jet Mimasu,Sanz 1409.4792, Haghighat,Raissi,Najafabadi 2006.05302 ATLAS 2102.10874, Ghebretinsae,Wang,Wang 2203.01734
- $pp \to W\gamma a, j\gamma a, t\bar{t}a, tja$ IB,Gavela,Merlo,Mimasu,No,delRey,Sanz 1701.05379 Ebadi,Khatibi,Najafabadi 1901.03061
- $Z \to a\gamma$ (also at LEP) IB,Gavela,Merlo,Mimasu,No,delRey,Sanz 1701.05379 Bauer,(Heiles),Neubert,Thamm 1708.00443,1808.10323

## Unstable, light

- $gg, \gamma\gamma \to a \to \gamma\gamma$ resonant in $pp$ Jäckel,Jankowiak,Spannowsky 1212.3620 (Cid Vidal),Mariotti,Redigolo,Sala,Tobioka 1710.01743, 1810.09452 Bauer,Heiles,Neubert,Thamm 1808.10323
- $\gamma\gamma \to a \to \gamma\gamma$ resonant in Pb-Pb Knapen,Lin,Lou,Melia 1607.06083,1709.07110 Baldenegro,Fichet,vonGersdorff,Royon 1803.10835 CMS 1810.04602, ATLAS 2008.05355
- $q\bar{q} \to W/Z/\gamma\, a, a \to \gamma\gamma$ Jäckel,Spannowsky 1509.00476 (Ren),Wang,Wu,Yang,Zhang 2102.01532, 2106.07018
- $pp \to a \to \tau\tau, \mu\mu, c\bar{c}(D)$ Cacciapaglia,Ferretti,Flacke,Serôdio 1710.11142 Buarque Franzosi,Cacciapaglia,Cid Vidal,Ferretti,Flacke,Sierra 2106.12615

## Unstable, heavy

- $pp \to aV_1 \to V_1V_2V_3$ $(V = W/Z/\gamma)$ resonant Craig,Hook,Kasko 1805.06538, CMS 1905.04246

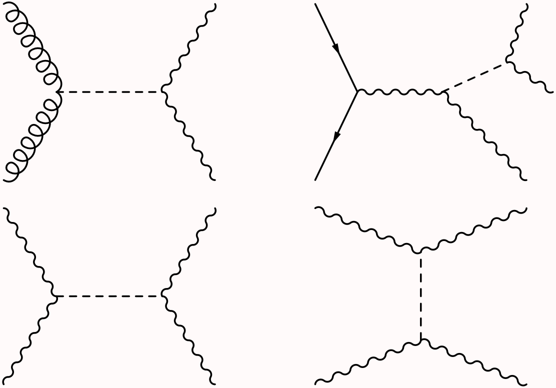
## Off-shell

- $gg \to a^* \to VV'$ non-resonant Gavela,No,Sanz,Trocóniz 1905.12953 Carrá, et al 2106.10085, CMS PAS B2G-20-013 2111.13669, Flórez, et al 2101.11119
- VBS non-resonant Bonilla,IB,Machado-Rodríguez,Trocóniz 2202.03450

# ALPs in multiboson

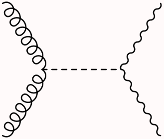
# Targeting ALP couplings to W, Z

Main value of VV(V) final states for ALPs: direct access to EW couplings



☞ ALP-fermion interactions suppressed @LHC except for top quark

# Heavy ALP: resonant searches



heavy alps can **decay resonantly** to WW, ZZ, $Z\gamma$

no reinterpretation of resonance searches available yet

☞ **inclusive** level: $\sigma(gg \to a) \times \mathrm{BR}(a \to ZZ) \;\sim\; g_{aGG}^2 \times \dfrac{g_{aVV}^2}{g_{aGG}^2 + g_{aVV}^2 + \ldots}$

one has to assume something, e.g. gluon dominance: Alonso-Álvarez,Gavela,Quilez 1811.05466

$g_{aGG} \gg g_{aVV}$, justified for QCD axion ($g_{aGG}/g_{a\gamma\gamma} \sim \alpha_s/\alpha$)

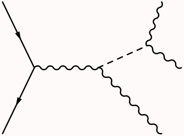
$\to \sigma(gg \to a) \times \mathrm{BR}(a \to ZZ) \;\sim\; g_{aVV}^2$

☞ **differential level**: $\neq$ "usual" pseudo-scalars (e.g. from 2HDM) has only effective, momentum dependent couplings

$$\cancel{a V_\mu V^\mu} \to a V_{\mu\nu} \tilde{V}^{\mu\nu}$$

$\gamma\gamma$ searches already account for this, but typically not WW and ZZ ones

# Constraints from tri-boson

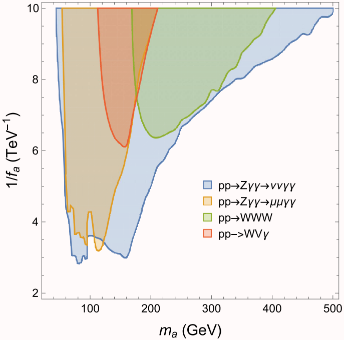


important resonant channel for "photophobic ALP":

$g_{agg} = 0 = g_{a\gamma\gamma}$ Craig,Hook,Kasko 1805.06538

→ only $WW, ZZ, Z\gamma$ decays allowed ($m_a \gtrsim 90\,\mathrm{GeV}$)

☞ several final states available and only 1 free parameter!

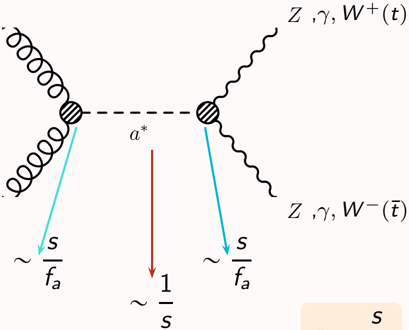


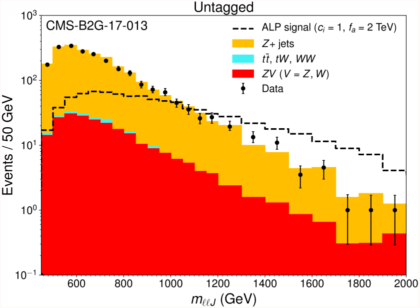
☞ could also be applied to the more general case (req. assumptions)

# Light ALP: Non-resonant searches

$ZZ, \gamma\gamma, t\bar{t}$: Gavela,No,Sanz,Troconiz 1905.12953, CMS PAS B2G-20-013 2111.13669
$WW, Z\gamma$: Carrá,Goumarre,Gupta,Heim,Heinemann,Küchler,Meloni,Quilez,Yap 2106.10085

ALP off-shell for $\boxed{m_a \ll m_1 + m_2 \leqslant \sqrt{s}}$ "too light to be resonant"





$$\rightarrow \boxed{\sigma \sim \frac{s}{f_a^4}}$$

<u>independent</u> of $m_a, \Gamma_a$

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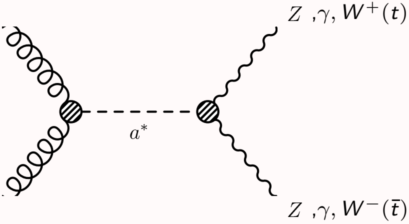
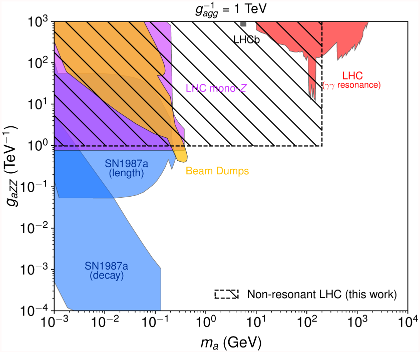




puts a constraint on $(g_{aGG} \times g_{aVV})$ product
for $g_{aGG}$ not too small, competitive bounds on $g_{aVV}$

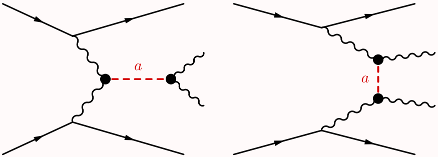
# Non-resonant searches in VBS

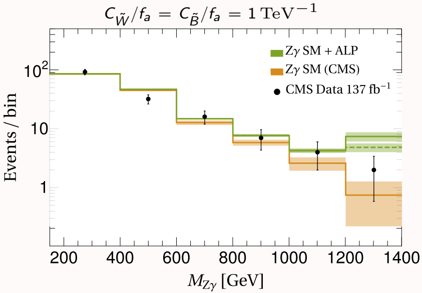
Bonilla, Brivio, Machado-Rodríguez, Trocóniz 2202.03450

same principle, applied to Vector Boson Scattering

→ **independent of $g_{aGG}$** (if pure ALP signal dominates, adding $C_{\tilde{G}}$ does not worsen bounds)

→ compare to actual analyses by CMS: $W^\pm W^\pm$, $W^\pm Z$, $W^\pm\gamma$, $Z\gamma$, $ZZ$





$$\sigma = \sigma_{SM} + \sigma_{\text{int.}}/f_a^2 + \sigma_{ALP}/f_a^4$$

$$\sigma_{\text{int.}} = C_{\tilde{B}}^2\,\sigma_{B2} + C_{\tilde{W}}^2\,\sigma_{W2} + C_{\tilde{B}}\,C_{\tilde{W}}\,\sigma_{WB}$$

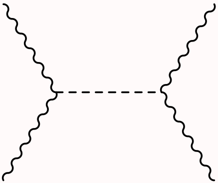
$$\sigma_{ALP} = C_{\tilde{B}}^4\,\sigma_{B4} + C_{\tilde{W}}^4\,\sigma_{W4} + C_{\tilde{B}}^2\,C_{\tilde{W}}^2\,\sigma_{W2B2} + C_{\tilde{B}}^3\,C_{\tilde{W}}\,\sigma_{B3W} + C_{\tilde{B}}\,C_{\tilde{W}}^3\,\sigma_{BW3}$$

Simulation done with Madgraph5 + `ALP_linear_UFO` feynrules.irmp.ucl.ac.be/wiki/ALPsEFT

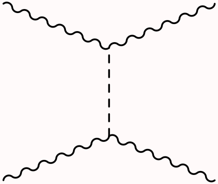
# Non-resonant searches in VBS: channels

| Ch. | Depends on | *Dist.* |
|---|---|---|
| $jjZZ$ | all | $m_{ZZ}$ |
| $jjZ\gamma$ | all | $m_{Z\gamma}$ |
| $jjW\gamma$ | only $c_{\tilde W}\neq 0$ | $m_{W\gamma}$ |
| $jjWZ$ | only $c_{\tilde W}\neq 0$ | $m^T_{WZ}$ |
| $jjW^\pm W^\pm$ | only $c_{\tilde W}$ | $m^T_{WW}$ |

all $137\,\mathrm{fb}^{-1}$ analyses except $W\gamma$ (36)



$ZZ$
$Z\gamma$

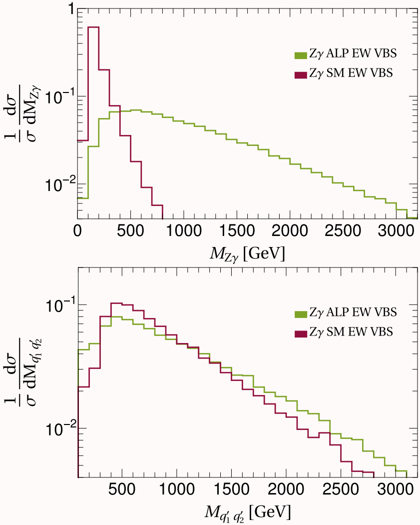


$ZZ$
$Z\gamma$
$W\gamma$
$WZ$
$W^\pm W^\pm$

# Non-resonant searches in VBS: channels

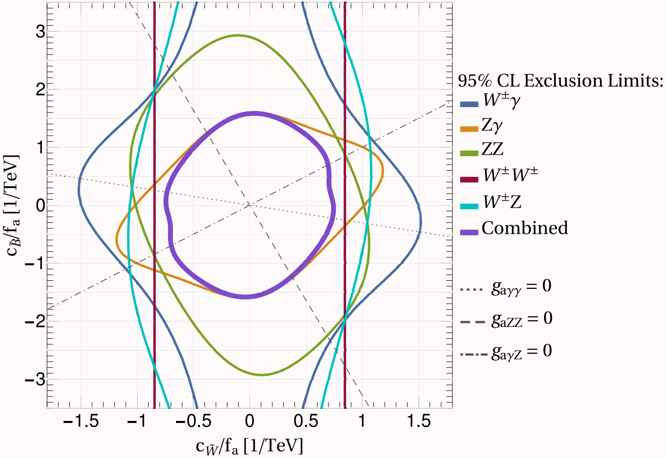
| Ch. | Depends on | *Dist.* |
|---|---|---|
| $jjZZ$ | all | $m_{ZZ}$ |
| $jjZ\gamma$ | all | $m_{Z\gamma}$ |
| $jjW\gamma$ | only $c_{\tilde{W}} \neq 0$ | $m_{W\gamma}$ |
| $jjWZ$ | only $c_{\tilde{W}} \neq 0$ | $m^T_{WZ}$ |
| $jjW^\pm W^\pm$ | only $c_{\tilde{W}}$ | $m^T_{WW}$ |

all $137\,\mathrm{fb}^{-1}$ analyses except $W\gamma$ (36)



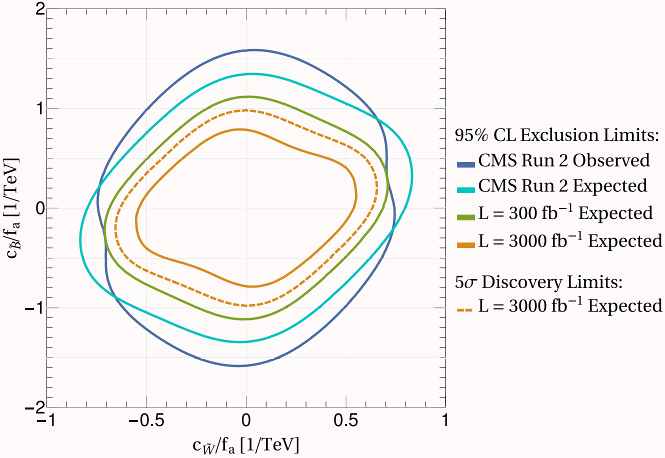
# Non-resonant searches in VBS: Run 2 results

**gauge invariant** param. → all EW couplings simultaneously accounted for



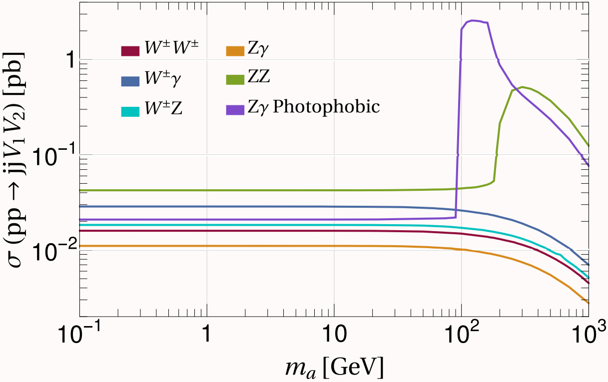
# Non-resonant searches in VBS: projections

HL-LHC: sensitivity improves $\times 5-8$ on XS → $\times 1.5-1.7$ on $C_i/f_a$



☞ this does not account for potential finer binning

# Dependence on ALP mass and width



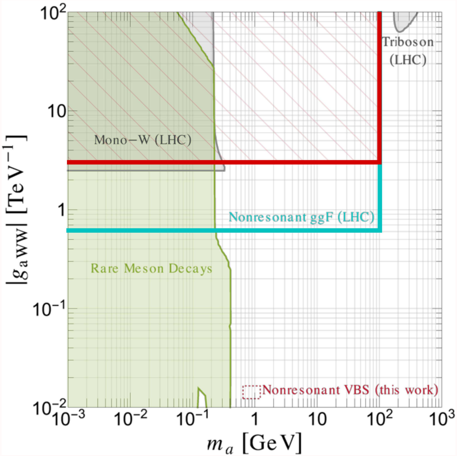
- as long as $q^2 \gg m_a, \Gamma_a$ , **independent** of exact values of mass and width
  "reverse" of an EFT ($q^2 \gg m^2$ vs $q^2 \ll m^2$ limit)
- XS stable up until $m_a \lesssim 100$ GeV

# Comparison with other constraints

main values

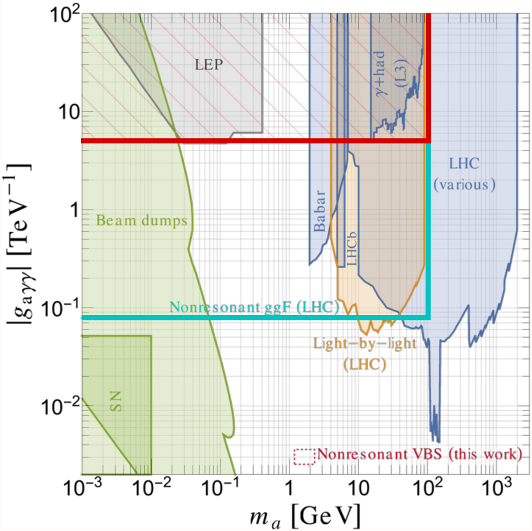
- strongest bound on $g_{aZZ}$, $g_{aWW}$ for $m_a \in [0.1, 100]$ GeV
- independent of $C_{\tilde{G}}$
- independent of $m_a, \Gamma_a$ as long as $<$ threshold

} relevant to break flat directions



# The need for a global approach

bounds typically represented in $(m_a, g_{aXX})$, but hide different assumptions
→ multi-dimensional, global analysis required



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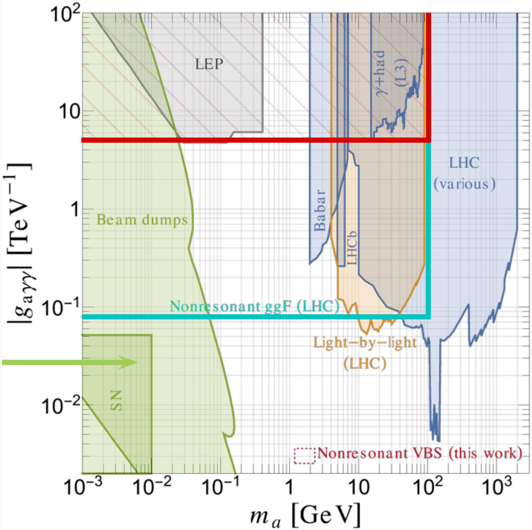
genuine



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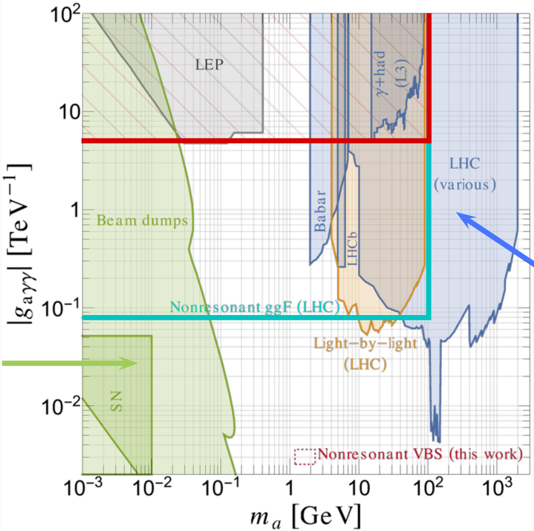

gluon dominance
$g_{agg} \gg g_{a\gamma\gamma}$

genuine

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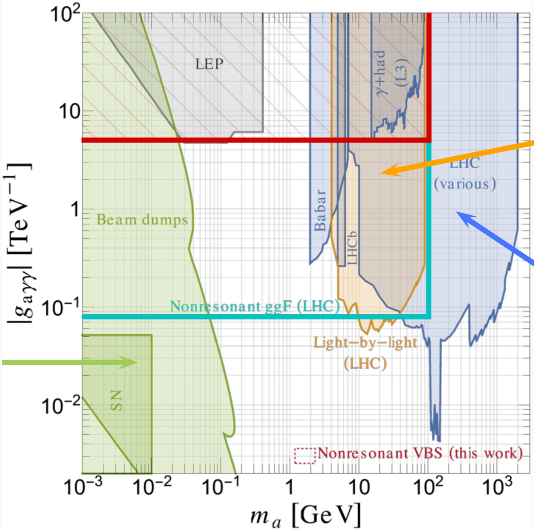

$\mathrm{BR}(a \to \gamma\gamma) = 1$
$(g_{agg} = 0 = g_{aff})$

gluon dominance
$g_{agg} \gg g_{a\gamma\gamma}$

genuine

# The need for a global approach

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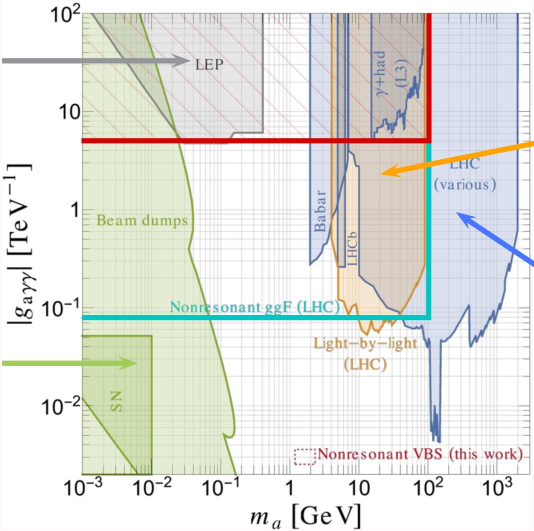
$\mathrm{BR}(a \to \gamma\gamma) = 1$
$(g_{aee} = 0)$

genuine



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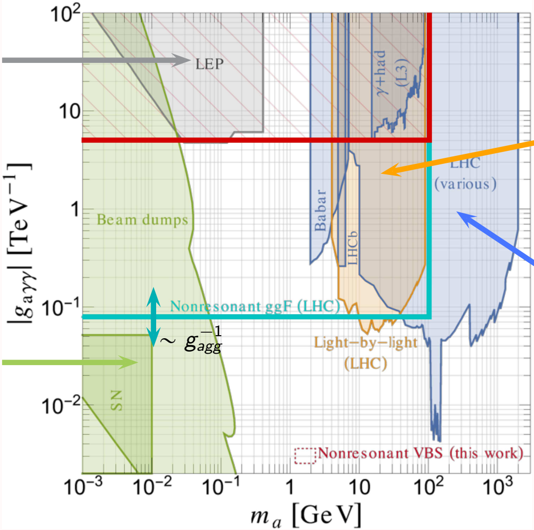

# Unitarity constraints

# Perturbative unitarity

very high energies involved @LHC. is the ALP EFT valid?

minimal EFT self-consistency ↔ preservation of perturbative unitarity

☞ **partial-wave unitarity** [defined for elastic scattering]

Jacob,Wick 1959

$$|T^J(V_1^{\lambda_1}V_2^{\lambda_2}\to V_1^{\lambda_1}V_2^{\lambda_2})|\overset{!}{\leqslant}1$$

unitarity violation at large $\sqrt{s}$ ⇒ **new dynamical states** must be included OR entering a **non-perturbative** regime

in ALP EFT: $|T^J|\sim\left[C_i\frac{\sqrt{s}}{f_a}\right]^n\left[\frac{\sqrt{s}}{m_W}\right]^m$ becomes $>1$ for large $\sqrt{s}$ or $(C_i/f_a)$

# Perturbative unitarity in ALP EFT

Strategy:

IB,Éboli,González-García 2106.05977
also: Corbett,Éboli,González-García 1411.5026,1705.09294

1. compute partial waves for all possible $2 \to 2$ processes in large $\sqrt{s}$ lim :

$$V_1 V_2 \to V_3 V_4 \qquad V_1 a \to V_2 a \qquad V_1 V_2 \to aa \qquad V_1 V_2 \to V_3 a$$
$$ha \to ha \qquad hh \to aa \qquad f_1 \bar{f}_2 \to Va$$

2. construct $T^{J=0}, T^{J=1}$ matrices in final states (particle and helicity) space → sorting processes by $Q$ and color contraction: block-diagonal

3. **diagonalize** $T^J$ matrices (block by block) → “overall” constraint on theory

4. apply elastic unitarity requirement $|T^J| \leqslant 1$ on each eigenvalue

# Unitarity constraints: results

even allowing all ALP couplings to vary simultaneously,
each is dominantly constrained by a different class of processes:

IB,Éboli,González-García 2106.05977

- ☞ $Va \to Va$, $ha \to ha$, $hh \to aa$ relevant only for dim-6 op. $O_\Phi^{(2)} = \partial_\mu a \partial^\mu a (H^\dagger H)$
- ☞ $f\bar{f} \to Va$ relevant only for $O_f$
- ☞ bounds on $O_{\tilde{G},\tilde{W},\tilde{B}}$ dominated by:

**VV→ VV**

$$\frac{|C_{\tilde{W}}|}{f_a} \lesssim 2.2\,\mathrm{TeV}^{-1}\left(\frac{\mathrm{TeV}}{\sqrt{s}}\right)$$

$$\frac{|C_{\tilde{B}}|}{f_a} \lesssim 5\,\mathrm{TeV}^{-1}\left(\frac{\mathrm{TeV}}{\sqrt{s}}\right)$$

$$\frac{|C_{\tilde{G}}|}{f_a} \lesssim 0.31\,\mathrm{TeV}^{-1}\left(\frac{\mathrm{TeV}}{\sqrt{s}}\right)$$

**VV→ Va**

$$\frac{|C_{\tilde{W}}|}{f_a} \lesssim 0.14\,\mathrm{TeV}^{-1}\left(\frac{\mathrm{TeV}}{\sqrt{s}}\right)$$ ③

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**VV→ Va**

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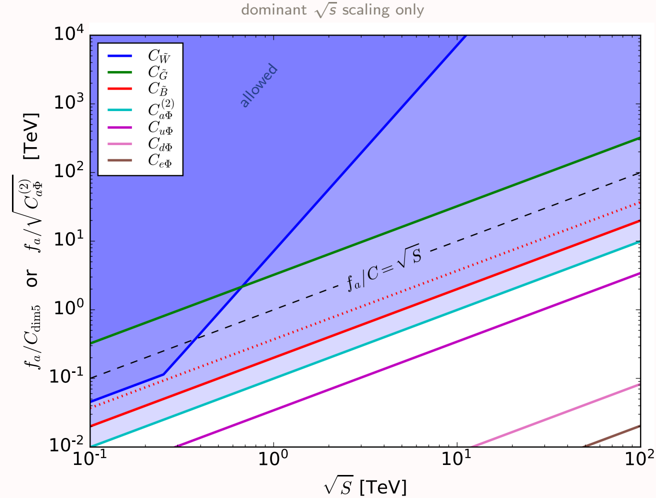
for all **VBS** channels & lumis:
setting $C_i/f_a$ to 95%CL boundary from fit
→ $<1$ event beyond unitarity bound
⇒ **safe**

# Unitarity constraints on ALP couplings



⚠ $\sqrt{s}$ overall scale, cannot be interpreted “literally” in specific processes

# Wrap-up

- ALPs are interesting! ubiquitous & discovery-friendly BSM/DM candidates
- a **very** rich phenomenology! thanks to wildly broad parameter space
- ALP EFT associated BSM sector integrated out
  → simple: limited # of parameters
  → non-trivial: shift-symmetry and anomalies complicate basis structure
- LHC crucial to probe **heavy** ALPs and couplings to **heavy** SM states
  → broad phenomenology, depending on mass and open decay channels
- new idea: search for non-resonant signals. explored in diboson and VBS
  → competitive bounds. independent of $m_a, \Gamma_a$ → cover large param. space
- perturbative unitarity considerations relevant for high-E (LHC) studies
  if an ALP is discovered, give an upper limit to NP scale