ALPs at Colliders

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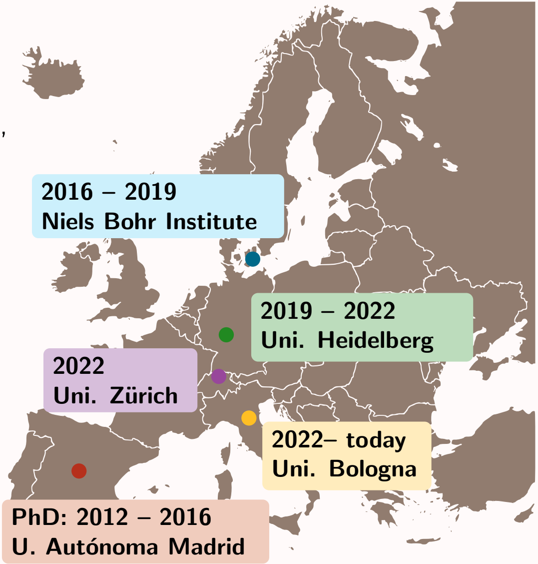
Career Recap

- research red thread: **Effective Field Theories for BSM**, mostly @LHC

  SMEFT, HEFT, ALPs. . .

- theory, but close contact with ATLAS/CMS exp

  LHC EFT Working Group [2020-2024]
  VBSCan COST Action [2018-2021]
  COMETA COST Action [2023-2027]



Axion-Like Particles

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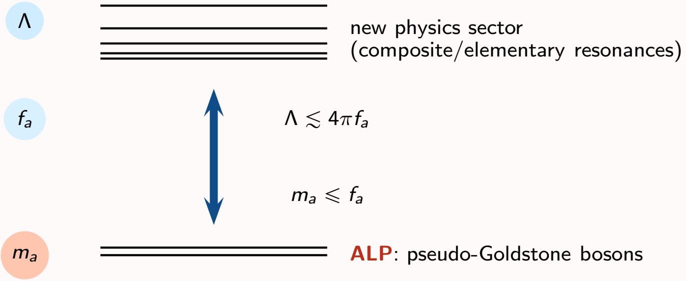
ALP = generic pseudo-Goldstone boson from breaking of BSM symmetry

Examples:

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



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Fundamental properties

- neutral, pseudo-scalar, couples to SM via effective interactions
- pseudo-Goldstone boson → $\mathbf{m_a}$ **naturally small** compared to NP scale

Why so interesting?

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

Original case study: QCD axion

strong CP problem

$\mathscr{L}_{SM} \supset \bar\theta \frac{g_s^2}{32\pi^2} G^A_{\mu\nu}\tilde G^{\mu\nu A} \to \not{CP}$ in QCD

neutron EDM requires $\bar\theta \lesssim 10^{-10}$

why so small?

"EFT" Axion solution

promote $\bar\theta$ to a dynamical field $\to$ $a(x)$ neutral pseudo-scalar, f_a scale to suppress dim-5 interaction

$$\mathscr{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G^A_{\mu\nu}\tilde G^{\mu\nu A} + \ldots$$

trick: proved that it must be $\langle a \rangle = 0 \Rightarrow$ no $\not{CP}$, but a new light DOF coupling to $G\tilde G$

UV origin: pseudo-Goldstone boson of Peccei-Quinn symmetry breaking

global, anomalous $U(1)_{PQ}$ defined such that $\partial_\mu J^\mu_{PQ} = \frac{g_s^2}{16\pi^2} N\, G^A_{\mu\nu}\tilde G^{\mu\nu A} + \ldots$

broken spontaneously $\to$ the resulting pGB satisfies the axion properties

The axion Lagrangian

- neutral pseudo-scalar
- **approx. shift symmetry** $a(x) \mapsto a(x) + c$ broken by the PQ anomaly ($aG\tilde{G}$ coupling)
- couples to SM via an **Effective Lagrangian** (dim $\geqslant 5$)
- mass and self-interactions generated non-perturbatively via shift symmetry breaking. naturally small compared to NP sector

$$\mathscr{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G^A_{\mu\nu}\tilde{G}^{\mu\nu A} + \frac{a}{f_a}\frac{e^2}{32\pi^2}\frac{E}{N} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\partial_\mu a}{2f_a}\bar{\psi}C_\psi \gamma^\mu\gamma_5\psi$$

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2} \sim \frac{10^{-6}\ \mathrm{GeV}^4}{f_a^2}$$

$+$ axion self-couplings, couplings to nucleons and mesons

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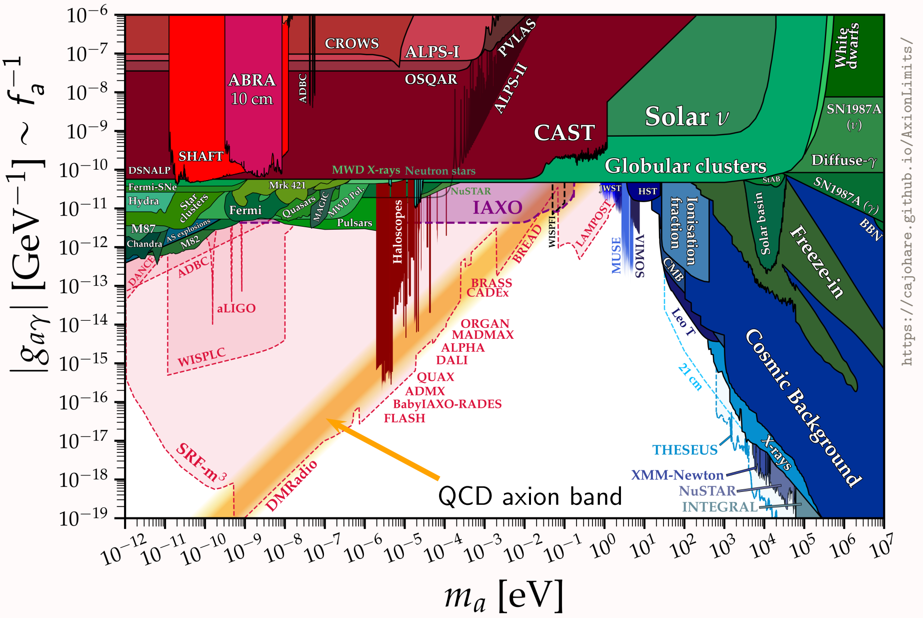
dependent on $U(1)_{PQ}$ realization

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2} \sim \frac{10^{-6}\ \mathrm{GeV}^4}{f_a^2}$$

consequence of axion solving strong CP

+ axion self-couplings, couplings to nucleons and mesons



$|g_{a\gamma}|\ [\mathrm{GeV}^{-1}] \sim f_a^{-1}$
m_a [eV]
CROWS
ALPS-I
OSQAR
PVLAS
ALPS-II
ABRA 10 cm
ADBC
SHAFT
DSNALP
CAST
Solar ν
Globular clusters
White dwarfs
SN1987A (ν)
Diffuse-γ
MWD X-rays
Neutron stars
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
Quasars
MAGIC
MWD Pol.
Pulsars
M87
Chandra
AS explosions
M82
NuSTAR
IAXO
Haloscopes
JWST
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NuSTAR
INTEGRAL
DANCE
ADBC
aLIGO
WISPLC
SRF-m^3
DMRadio
BRASS
CADEx
ORGAN
MADMAX
ALPHA
DALI
QUAX
ADMX
BabyIAXO-RADES
FLASH
QCD axion band
https://cajohare.github.io/AxionLimits/

ALP Effective Field Theory

- most general EFT of ALP interactions: 👉 $SU(3)\times SU(2)\times U(1)$ invariant (for LHC applications)
  👉 fields: SM states + ALP
- **shift symmetry**: here assume broken only by m_a, but more operators could enter
- assume CP invariance, but CP-odd couplings could be inserted too review: di Luzio,Levati,Paradisi,Sørensen 2312.17310

$$\mathcal{L}_{ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + C_i O_i^{(5)} + \mathcal{O}(f_a^{-2})$$

Georgi,Kaplan,Randall PLB169B(1986)73

$$O_{\tilde{B}} = \frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$O_{\tilde{W}} = \frac{a}{f_a} W^I_{\mu\nu}\tilde{W}^{I\mu\nu}$$

$$O_{\tilde{G}} = \frac{a}{f_a} G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

$$O_{f,ij} = \frac{\partial^\mu a}{f_a}(\bar{f}_i\gamma^\mu f_j), \qquad f = Q_L, u_R, d_R, \ell_L, e_R$$

Parameter space of the ALP EFT at dim-5

Free quantitites			$N_f = 1$	$N_f = 3$
m_a			1	1
C_i/fa :	$C_{\tilde{B}}, C_{\tilde{W}}, C_{\tilde{G}}$	$\in \mathbb{R}$	3	3
	$C_{f,ij}$	$\in N_f \times N_f$ symmetric $\mathbb{R}$ matrices	5×1	5×6
		$-L_i$ rotations	-1	-3
		$-(B-L)$ rotation	-1	-1
			7	**30**

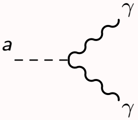
redundancies due to:

$$\frac{\partial_\mu a}{f_a} J^\mu_{L_i} = O_{\ell,ii} + O_{e,ii} = \frac{1}{32\pi^2}\left[g^2 O_{\tilde{W}} - g'^2 O_{\tilde{B}}\right]$$

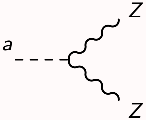
$$\frac{\partial_\mu a}{f_a} J^\mu_{B-L} = \frac{1}{3}\mathrm{Tr}[O_Q + O_u + O_d] - \mathrm{Tr}[O_\ell + O_e] = 0$$

[only visible in 1-loop calculations] Chala,Guedes,Ramos,Santiago 2012.09017, Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272 Bonilla,IB,Gavela,Sanz 2107.11392, Bonnefoy,Grojean,Kley 2206.04182

ALP couplings to dim-5



$\sim (s_\theta^2 \mathbf{C}_{\tilde{W}} + c_\theta^2 \mathbf{C}_{\tilde{B}})$



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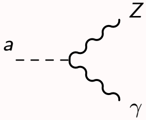
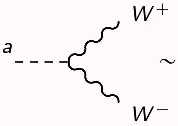
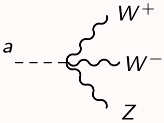


$\sim s_{2\theta}(\mathbf{C}_{\tilde{W}} - \mathbf{C}_{\tilde{B}})$



$\sim \mathbf{C}_{\tilde{W}}$



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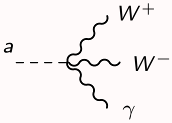

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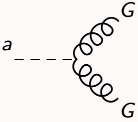
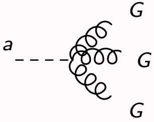


$\sim \mathbf{C}_{\tilde{G}}$



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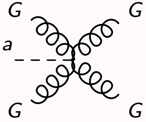

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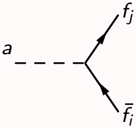
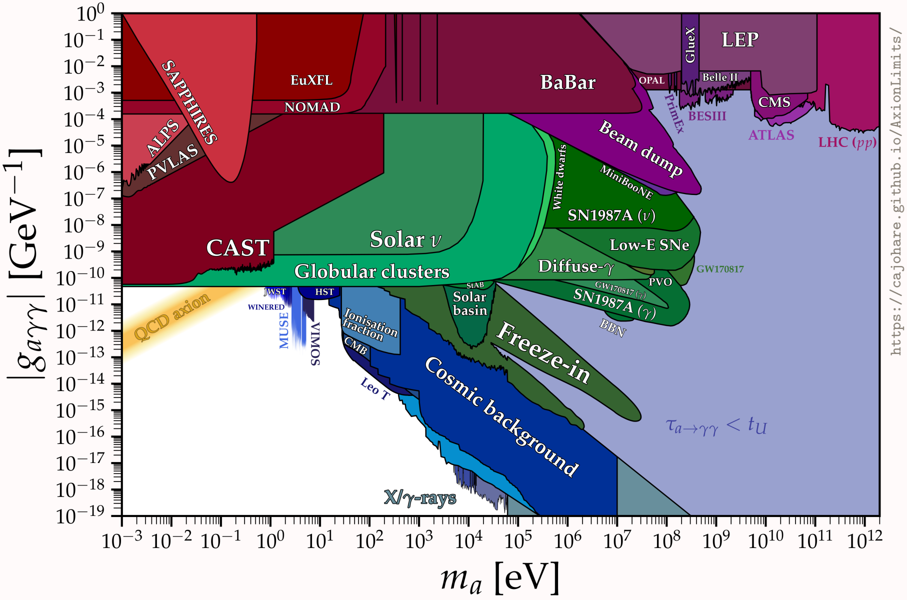


$\sim \mathbf{C}_{\mathrm{fij}}$

ALPs at Colliders (LHC)



SAPPHIRES
EuXFL
NOMAD
BaBar
GlueX
LEP
OPAL
Belle II
PrimEx
BESIII
CMS
ATLAS
LHC (pp)
ALPS
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$|g_{a\gamma\gamma}|$ [GeV^{-1}]
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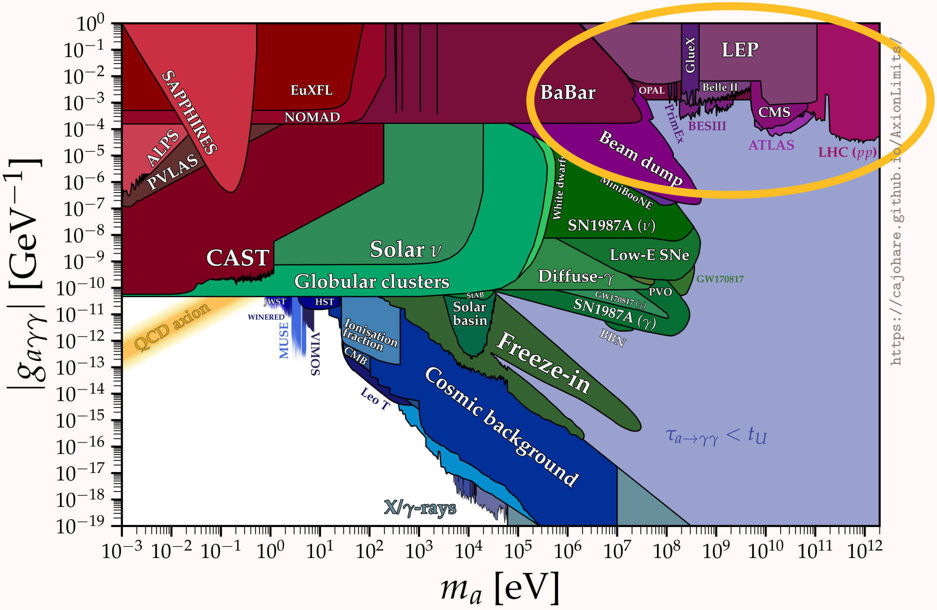
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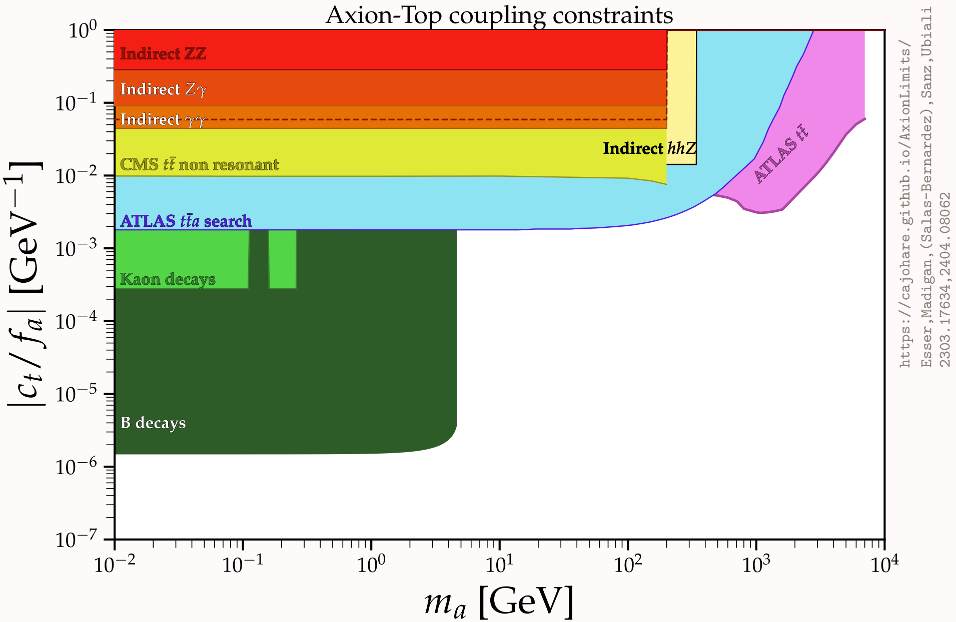


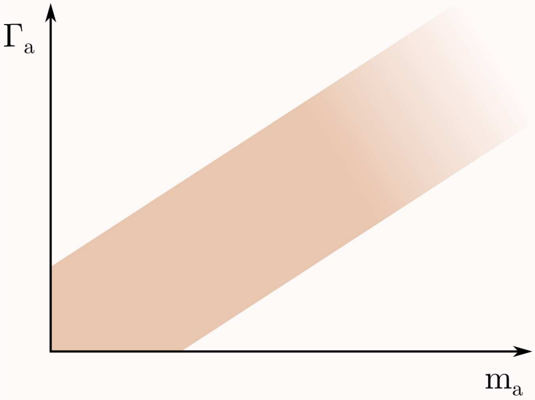
Axion-Top coupling constraints
Indirect ZZ
Indirect $Z\gamma$
Indirect $\gamma\gamma$
CMS $t\bar{t}$ non resonant
Indirect hhZ
ATLAS $t\bar{t}a$ search
ATLAS $t\bar{t}$
Kaon decays
B decays
$|c_t/f_a|$ [GeV^{-1}]
m_a [GeV]
https://cajohare.github.io/AxionLimits/
Esser,Madigan,(Salas-Bernardez),Sanz,Ubiali
2303.17634,2404.08062

Collider probes of the ALP parameter space

Motivation

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

Signatures



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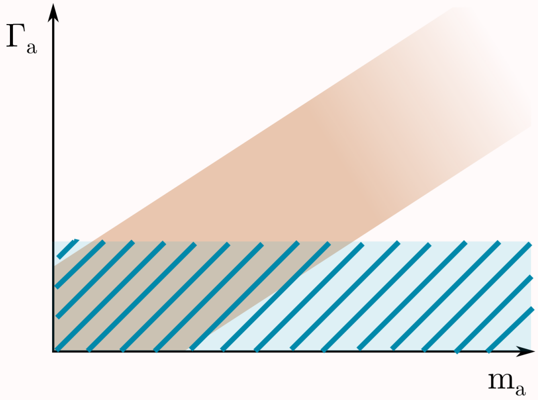
stable ALP

↓

$\not{E}_T$



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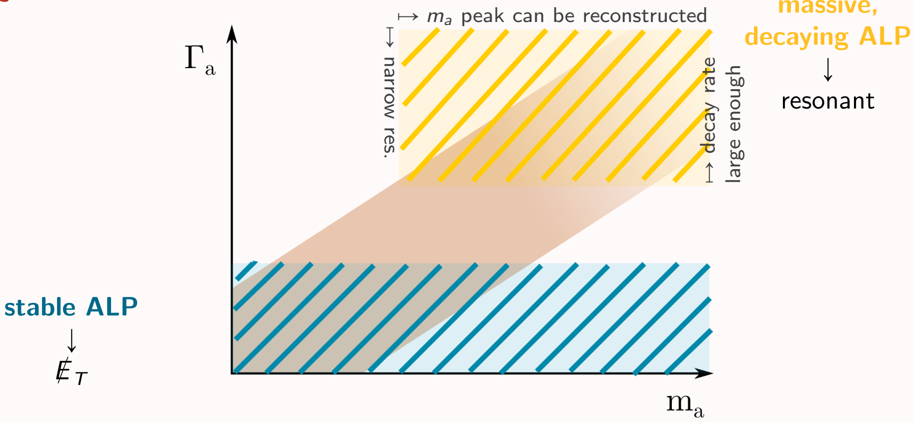

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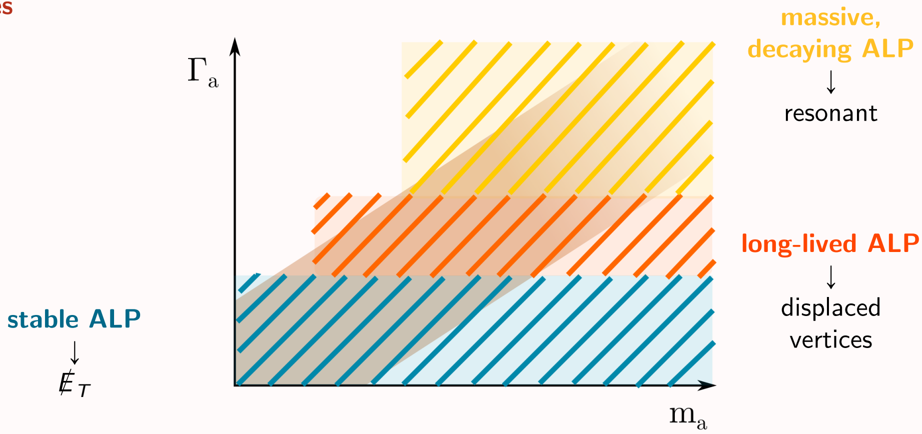

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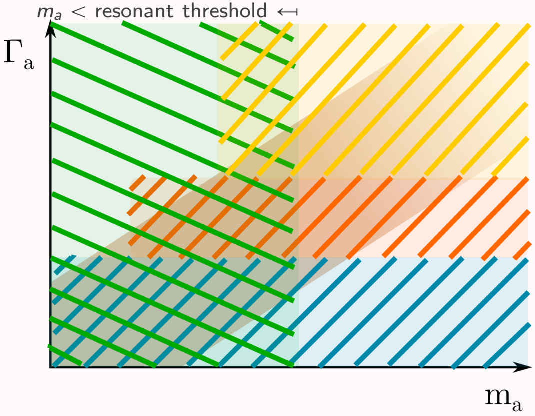
Signatures

off-shell ALP
↓
non-resonant

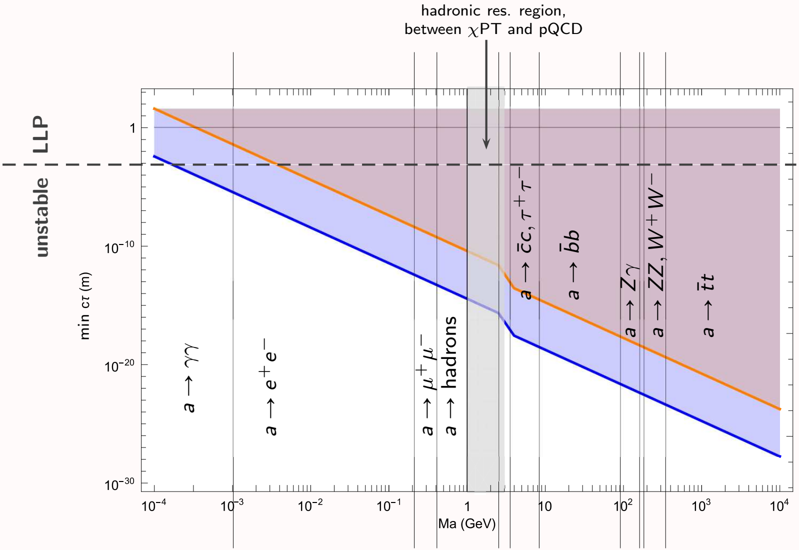
stable ALP
↓
$\not{E}_T$



massive, decaying ALP
↓
resonant

long-lived ALP
↓
displaced vertices

ALP decay modes and lifetime



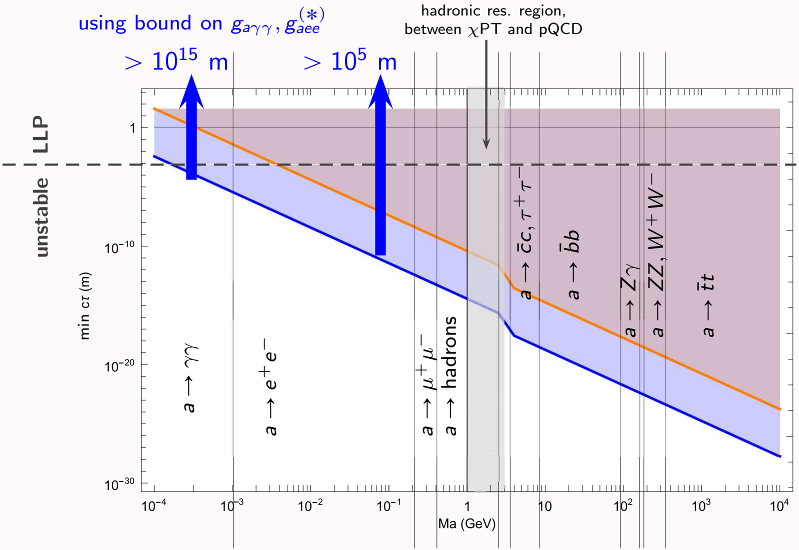
$$\Gamma_{a\to V_1 V_2} \sim \mathbf{m_a^3} \frac{C_i^2}{f_a^2}$$

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

$\frac{C_i}{f_a} < 10^3\ \text{TeV}^{-1}$ (blue)

$\frac{C_i}{f_a} < 10\ \text{TeV}^{-1}$ (orange)

ALP decay modes and lifetime



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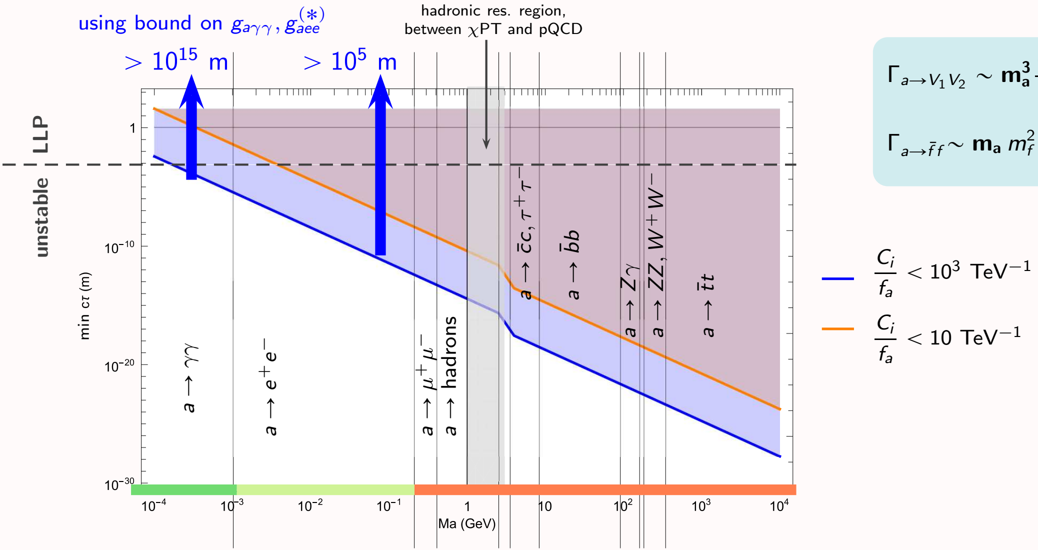
ALP decay modes and lifetime



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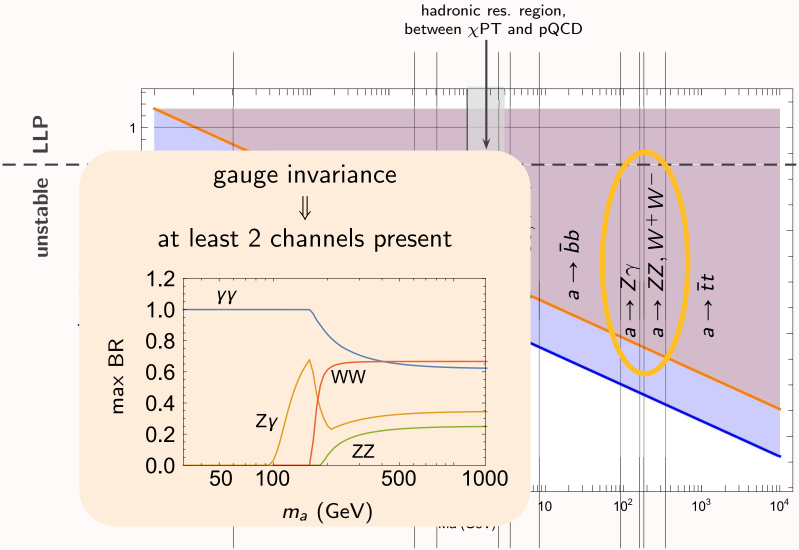
$$\Gamma_{a\to \bar{f}f} \sim \mathbf{m_a}\, m_f^2 \frac{C_f^2}{f_a^2}$$

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

$m_a > 200\,\mathrm{MeV}$ assuming stability restrict space

ALP decay modes and lifetime



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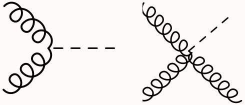
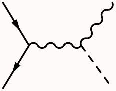
$\frac{C_i}{f_a} < 10\ \text{TeV}^{-1}$

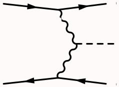
ALP at LHC: main production modes



$gg \to a(g)$ — $C_{\tilde{G}}$

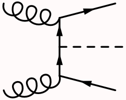


$q\bar{q} \to Va,\ V = Z, W^{\pm}, \gamma$ — $C_{\tilde{B}}, C_{\tilde{W}}$



$q\bar{q} \to q\bar{q}a$ — $C_{\tilde{B}}, C_{\tilde{W}}, C_{\tilde{G}}$

also: light-by-light



$gg \to \bar{t}ta$ — C_f

ALP at LHC: main production modes

Depending on ALP mass: production via **decays of SM** states.

$$Z \to a\gamma \qquad \mathbf{C}_{\tilde{B}}, \mathbf{C}_{\tilde{W}}$$

Depending on presence of flavor violating couplings, or at 1-loop:

$\psi_1 \to a\psi_2$	$\mathbf{C}_f, \mathbf{C}_{\tilde{W}}$	
$\psi_1 \to a\psi_2\gamma$	$\mathbf{C}_f, \mathbf{C}_{\tilde{W}}$	
$M_1 \to aM_2$	$\mathbf{C}_f, \mathbf{C}_{\tilde{G}}, \mathbf{C}_{\tilde{W}}, \mathbf{C}_{\tilde{B}}$	M_1, M_2 mesons, e.g. $B \to aK, K \to a\pi \ldots$
$M \to a\gamma$	$\mathbf{C}_f, \mathbf{C}_{\tilde{G}}, \mathbf{C}_{\tilde{W}}, \mathbf{C}_{\tilde{B}}$	

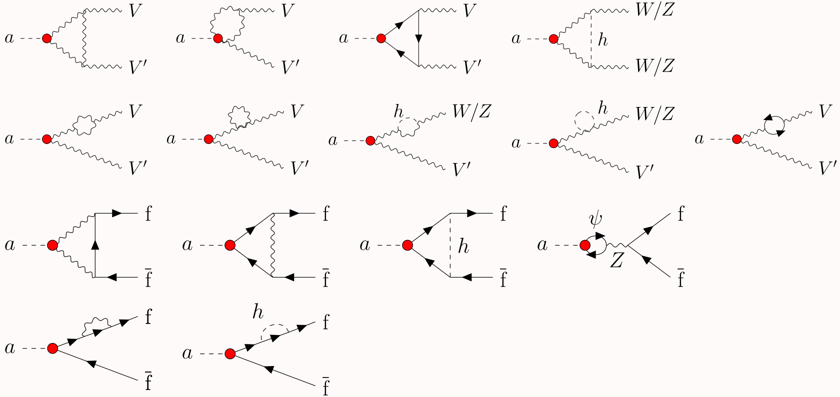
☞ very rich ALP phenomenology in **flavor physics**, not touched upon here

ALP EFT at 1-loop

in general, large “mixing” among coefficients at 1-loop:

each ALP coupling receives **loop corrections from most ALP parameters**

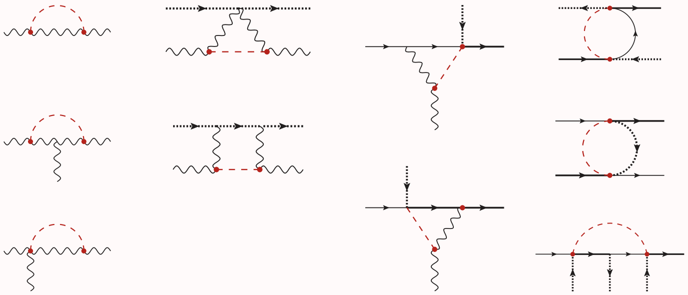
Bonilla,IB,Gavela,Sanz 2107.11392
Bauer,Neubert,Thamm 1708.00443
Bauer,Neubert,Renner, Schnubel,Thamm 2012.12272



ALP EFT at 1-loop

in general, large "mixing" among coefficients at 1-loop:

dim-5 ALP operators also mix into dim-6 SMEFT ones with $\Lambda = 4\pi f_a$ Galda,Neubert,Renner 2105.01078



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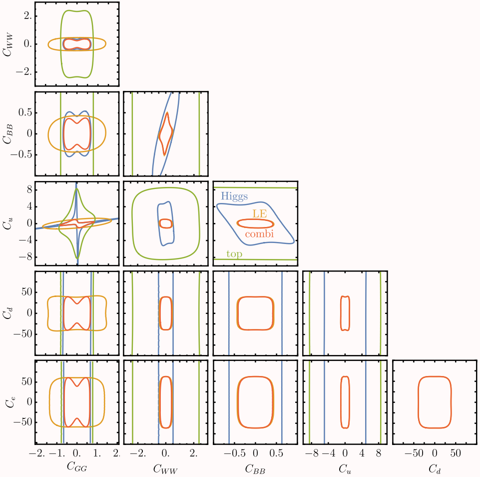


Biekötter,Fuentes-Martin,Galda,Neubert 2307.10372

Collider signals of flavor conserving, dim-5 couplings

incomplete list! omitting Higgs. flavor viol., ATLAS/CMS

Stable

- mono-Z, mono-W, mono-γ, mono-jet, di-jet
- $pp \to W\gamma a, j\gamma a, t\bar{t}a, tja, tWa$
- $Z \to a\gamma$ (also at LEP)

Mimasu,Sanz 1409.4792, IB+ 1701.05379, Haghighat+ 2006.05302, Haisch+ 2107.12839, Esser+ 2303.17634, Blasi+ 2311.16048, Hosseini,Najafabadi 2408.11588, Ghebretinsae+ 2203.01734, Ebadi+ 1901.03061, Rygaard+ 2306.08686, Bauer+ 1708.00443,1808.10323

Unstable light

- $gg, \gamma\gamma \to a \to \gamma\gamma$ resonant in pp
- $\gamma\gamma \to a \to \gamma\gamma$ resonant in Pb-Pb
- $q\bar{q} \to W/Z/\gamma\, a, \;\; a \to \gamma\gamma$
- $pp \to a \to \tau\tau, \mu\mu, c\bar{c}(D)$

Jäckel+ 1212.3620
Mariotti+ 1710.01743, 1810.09452 Knapen+ 1607.06083,1709.07110
Baldenegro+ 1803.10835 Jäckel,Spannowsky 1509.00476
Wang+ 2102.01532, 2106.07018 Cheung+ 2402.10550
Cacciapaglia+ 1710.11142, 2106.12615

Unstable heavy

- $pp \to aV_1 \to V_1V_2V_3$ ($V = W/Z/\gamma$) resonant
- $pp \to a \to t\bar{t}$ resonant

Craig,Hook,Kasko 1805.06538
Anuar+ 2404.19014, Aiko+ 2401.13323

Nonres.

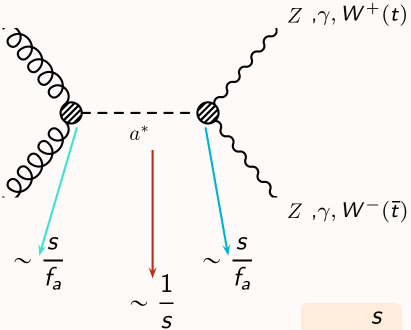
- $gg \to a^* \to VV', \bar{t}t$ non-resonant
- VBS non-resonant

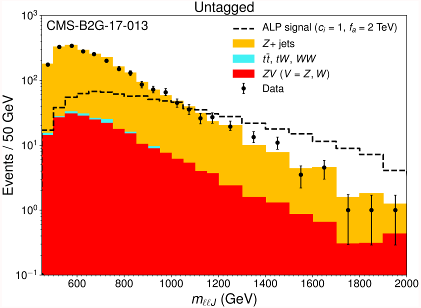
Gavela+ 1905.12953 Carrá+ 2106.10085, Flórez+ 2101.11119, Bonilla,IB+ 2202.03450

Non-resonant ALP signals at LHC

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 $m_a \ll m_1 + m_2 \leqslant \sqrt{s}$ "too light to be resonant"





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

independent of m_a, Γ_a

Non-resonant ALP signals at LHC

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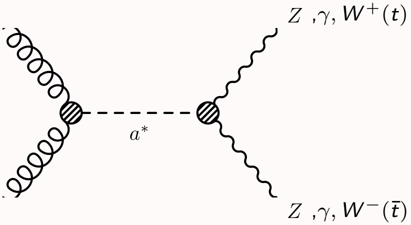
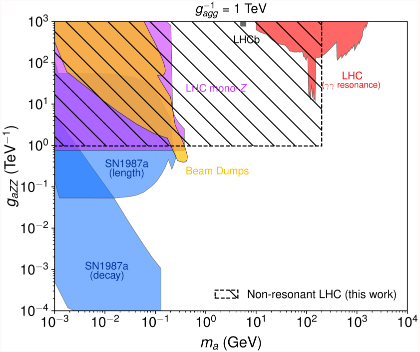




puts a constraint on $(g_{aGG} \times g_{aVV})$ product

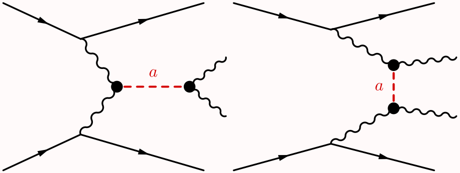
for g_{aGG} not too small, competitive bounds on g_{aVV}

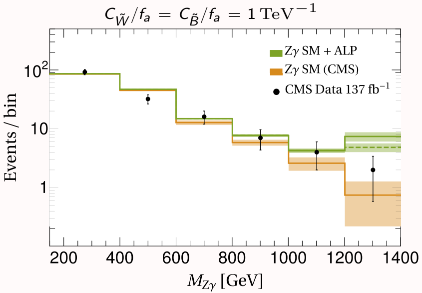
Bonilla, IB, Machado-Rodríguez, Trocóniz 2202.03450

apply same principle to Vector Boson Scattering

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

→ a nice playground with several final states constraining the same 2 couplings





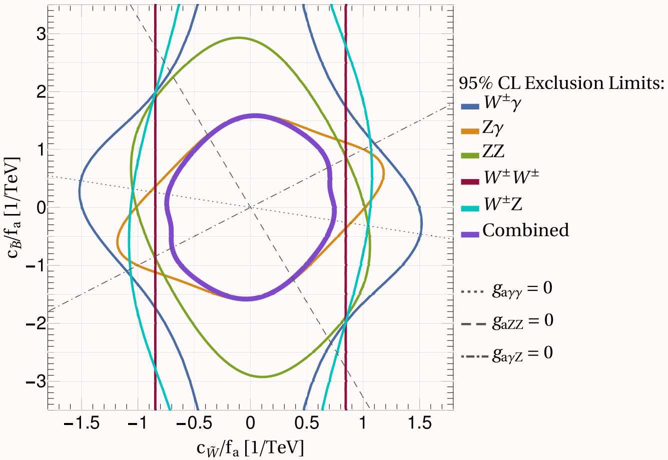
$$\sigma = \sigma_{SM} + \sigma_{\rm int.}/f_a^{2} + \sigma_{ALP}/f_a^{4}$$

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

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

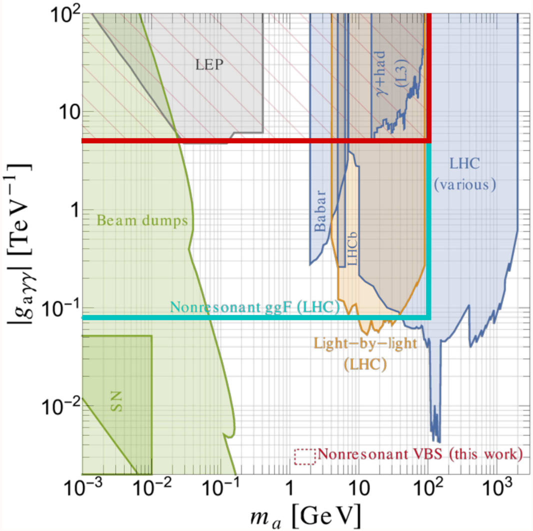
Non-resonant searches in VBS: Run 2 results

bounds extracted comparing to Run-2 CMS measurements



Comparing bounds, with a grain of salt

bounds typically represented in (m_a, g_{aXX}), but hide different assumptions



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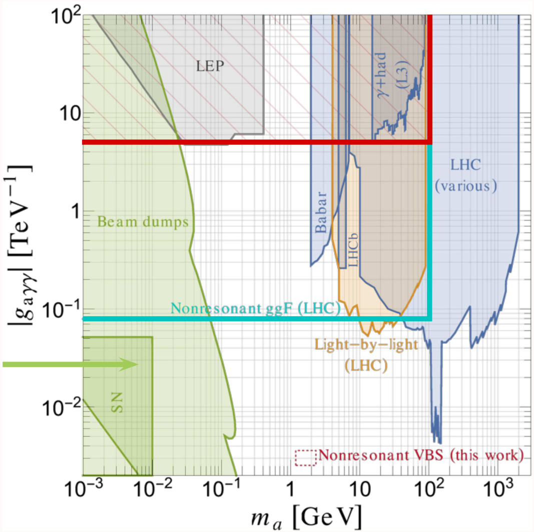
genuine



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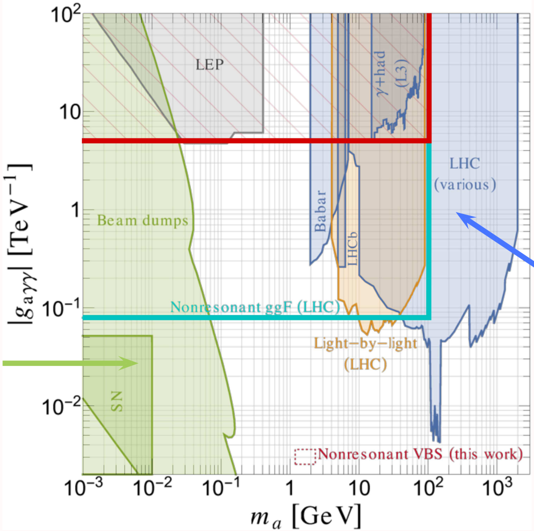

gluon dominance
$g_{agg} \gg g_{a\gamma\gamma}$

genuine

Comparing bounds, with a grain of salt

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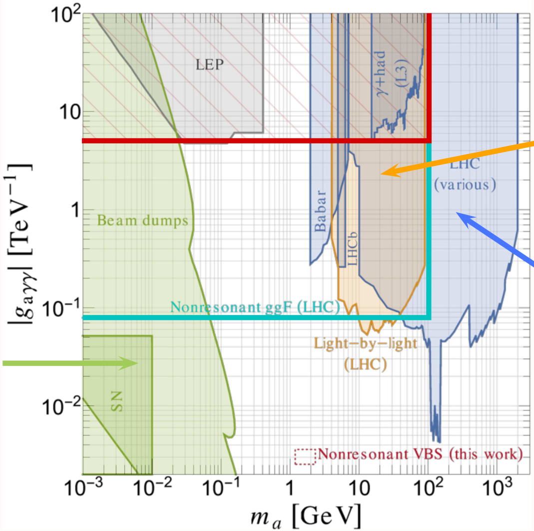

$\mathrm{BR}(a \to \gamma\gamma) = 1$
$(g_{agg} = 0 = g_{aff})$

gluon dominance
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genuine

Comparing bounds, with a grain of salt

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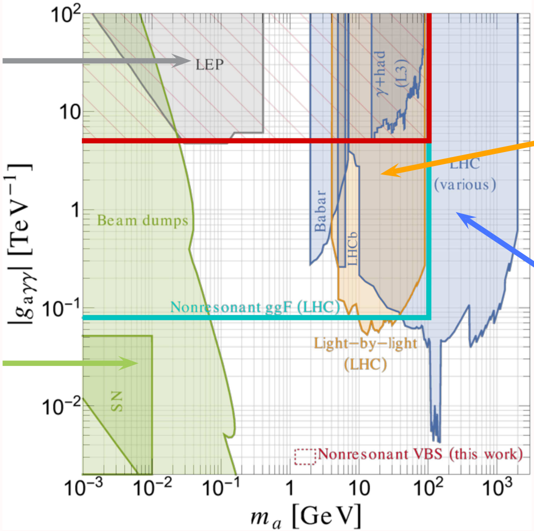

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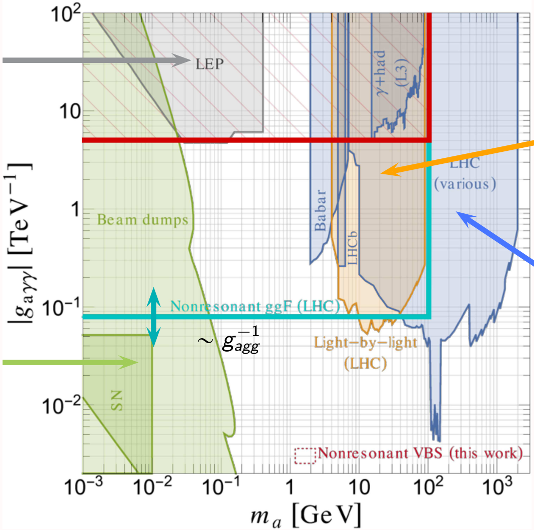

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genuine

Unitarity constraints on ALP couplings

IB,Éboli,González-García 2106.05977

How much can we rely on s enhancements? Does the EFT stay valid?

perturbative unitarity requires

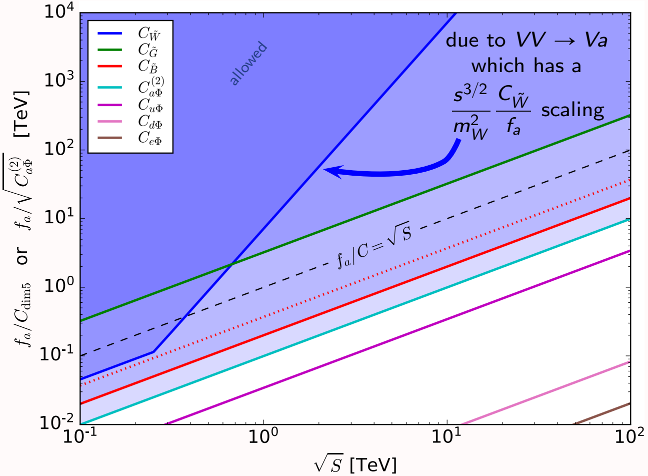
$$|T^J| \sim \beta \frac{\sqrt{s}C_i}{f_a} + \ldots \leqslant 1$$

β some constant,

$\ldots$ = subleading orders in s

$\Downarrow$

only **colored regions** are physical



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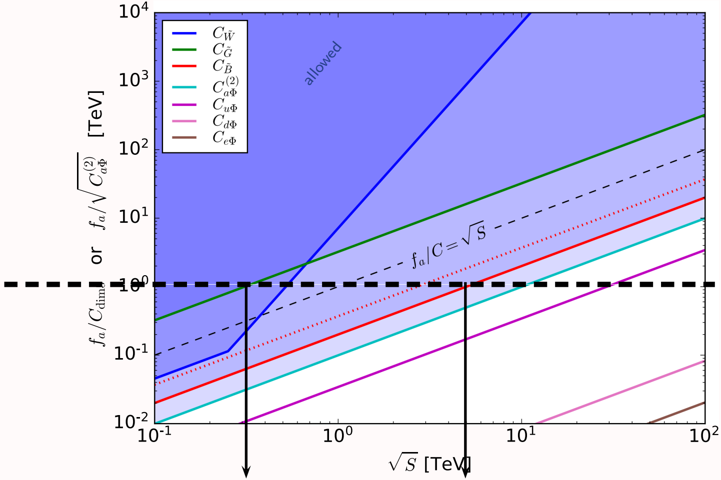


an EFT with

$f_a/C_i = 1\,\text{TeV}$

requires NP

at most at

$310\,\text{GeV}$ $(C_{\tilde G})$ $5\,\text{TeV}$ $(C_{\tilde B})$

Unitarity constraints on ALP couplings

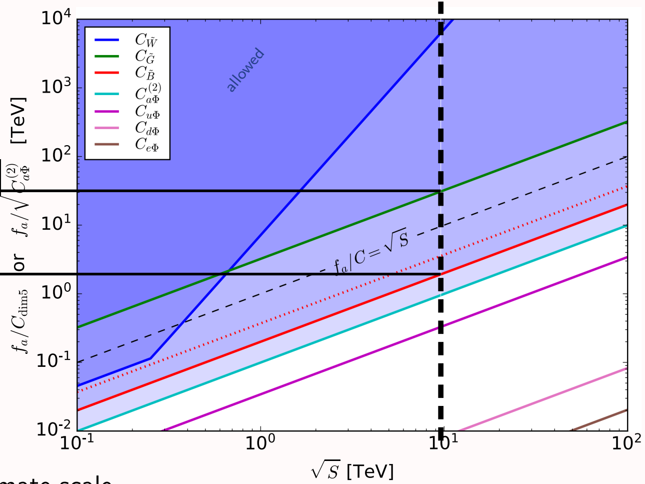
IB, Éboli, González-García 2106.05977

How much can we rely on s enhancements? Does the EFT stay valid?

a measurement at
$\sqrt{s} \simeq 10\,\text{TeV}$
can only probe:

$f_a/C_{\tilde{G}} > 32\,\text{TeV}$

$f_a/C_{\tilde{B}} > 2\,\text{TeV}$



⚠ here: $\sqrt{s}$ approximate scale

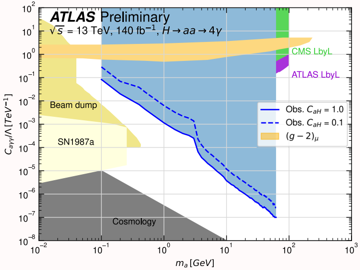
ALP EFT to higher orders

Operator bases (with and without shift-symmetry) were built up to dim-8 — Bonnefoy, Grojean, Kley 2206.04182; Grojean, Kley, Yao 2307.08563

dim-6 contains a unique shift-invariant operator $\frac{1}{f_a^2}\partial_\mu a \partial^\mu a\, H^\dagger H$

which introduces **couplings to the Higgs**: aah , $aahh$ and is the first operator with **2 ALPs**

- rich phenomenology, incl. implications for ALP production in early universe — Bauer, Rostagni, Spinner 2207.05762
- for $m_a < m_h/2$, causes $h \to aa$
  $\Rightarrow h \to$ inv, stable ALP
  $h \to$ exotic channels $(4\gamma \ldots)$, unstable ALP
  Bauer, Neubert, Thamm 1708.00443
  ATLAS-CONF-2023-040
- enters meson decays as $M_1 \to M_2 aa$, $M^0 \to aa(\gamma)$



ALP EFT to (even) higher orders

dim-7 contains many more shift-invariant operators (5 w/o fermions), all with 1 ALP insertion

most notably, at this order the **aZh, aZhh couplings** appear, from $\partial_\mu a(H^\dagger i\overleftrightarrow{D}_\mu H)H^\dagger H$

- depending on m_a, it allows $h \to Za,\ a \to Zh$

IB et al 1701.05379, Bauer et al 1708.00443
Cheung,Ouseph 2402.05678

- mediates mono-Higgs $pp \to Z^* \to ah$ and ahh
- can induce non-resonant $pp \to a* \to hhZ$

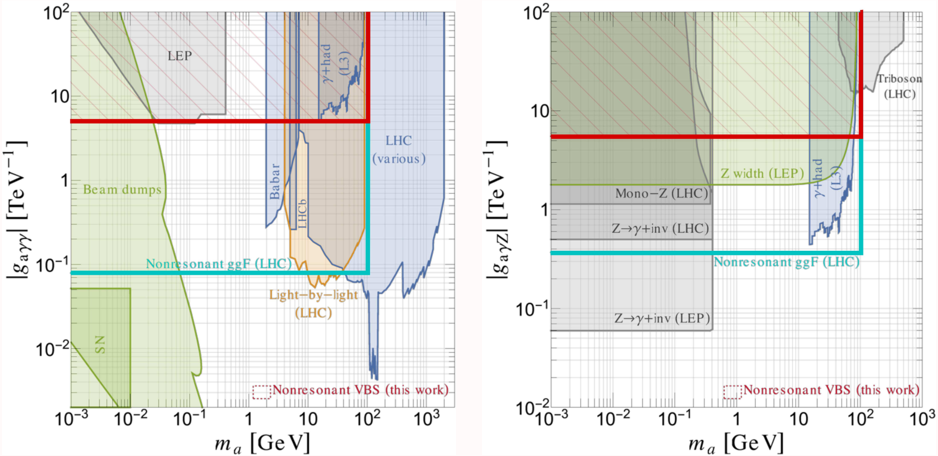
Esser,Madigan,Salas-Bernardez,Sanz,Ubiali 2404.08062

ALP EFT wrap-up

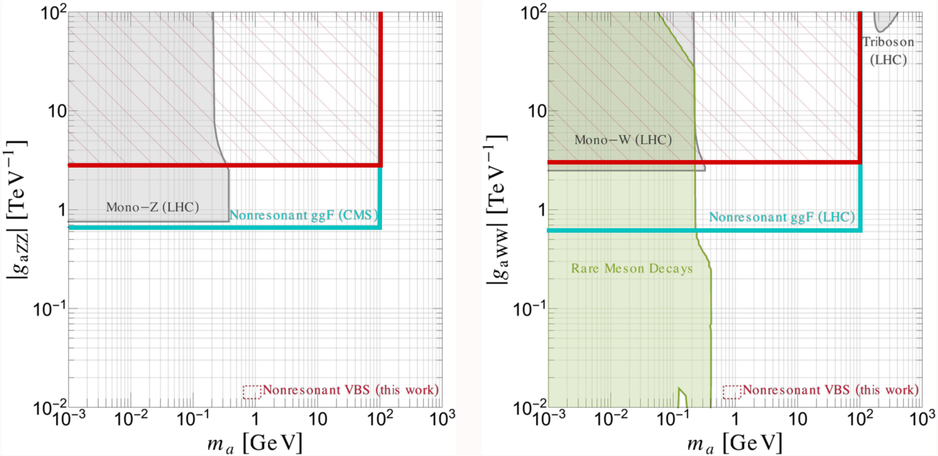
- ALPs are interesting! ubiquitous & discovery-friendly BSM/DM candidates
- a **very** rich phenomenology! thanks to wildly broad parameter space
- ALP EFT associated BSM sector integrated out
  → simple: limited # of parameters
  → non-trivial: shift-symmetry and anomalies complicate basis structure
  → interesting interplays at loop level
- Colliders crucial to probe **heavy** ALPS and couplings to **heavy** SM states
  → broad phenomenology, depending on mass and open decay channels
- perturbative unitarity considerations relevant for high-E (LHC) studies
  if an ALP is discovered, give an upper limit to NP scale
- several colliders searches performed, many ideas applied.
  non-resonant signals in heavy final states particularly suited for ALPs

Backup slides

Bounds on ALP couplings

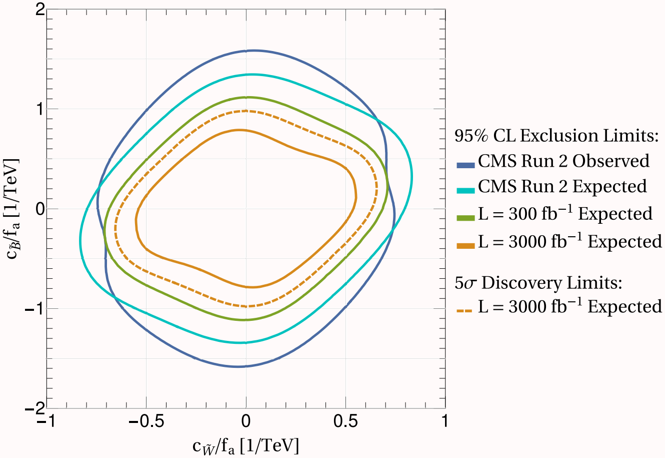


Bounds on ALP couplings

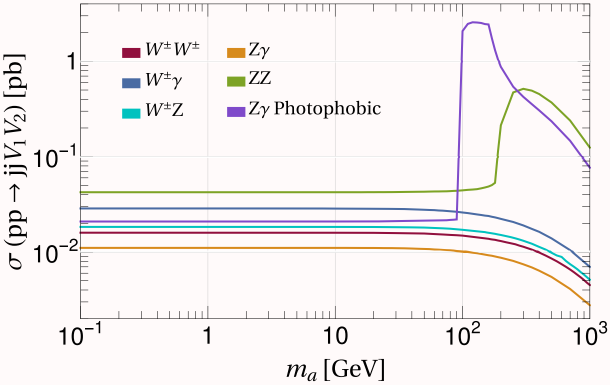


Non-resonant searches in VBS: projections

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



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

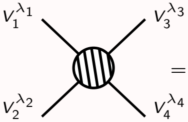
Perturbative unitarity

partial-wave decomposition for $2 \to 2$ scattering: Jacob,Wick 1959

V_i = vector bosons or scalars

λ_i = helicities (V:$\lambda_i = 0, \pm 1$, S:$\lambda_i \equiv 0$), $\lambda = \lambda_1 - \lambda_2, \mu = \lambda_3 - \lambda_4$

T^J = amplitude for J-wave scattering



$$= 16\pi \sum_J (2J+1)\sqrt{1+\delta_{V_1\lambda_1}^{V_2\lambda_2}}\sqrt{1+\delta_{V_3\lambda_3}^{V_4\lambda_4}}\, e^{i(\lambda-\mu)\phi} d^J_{\lambda\mu}(\theta)\; T^J(V_1^{\lambda_1} V_2^{\lambda_2} \to V_3^{\lambda_3} V_4^{\lambda_4})$$

unitarity = $|T^J(V_1^{\lambda_1} V_2^{\lambda_2} \to V_1^{\lambda_1} V_2^{\lambda_2})| \leqslant 1$ for $s \gg (M_1 + M_2)^2$

[defined for *elastic* scattering]

unitarity violation = unphysical pred.
- → the theory is not valid: new dynamical **states** must be included
- → pert. expansion is not valid: 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

Calculation strategy

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

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

$$V_1V_2 \to V_3V_4 \qquad V_1 a \to V_2 a \qquad V_1V_2 \to aa \qquad V_1V_2 \to V_3 a$$
$$ha \to ha \qquad hh \to aa \qquad f_1\bar{f}_2 \to Va$$

2. construct $T^{J=0}$, $T^{J=1}$ matrices in final states (particle and helicity) space
   $\to$ block-diagonal classifying processes by Q and color contraction
3. **diagonalize** T^J matrices $\to$ "overall" constraint on theory
4. apply elastic unitarity requirement $|t^J| \leqslant 1$ on each eigenvalue

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Constraints identified allowing all operators simultaneously.

- $O_{\tilde{W}}$ dominated by T^1 from $VV \to Va$, scaling as $C(\sqrt{s})^3/(f_a m_W^2)$
- $O_{\tilde{B}}, O_{\tilde{G}}$ dominated by T^0 from $VV \to VV, aa$, scaling as $(C\sqrt{s}/f_a)^2$
- O_{fH} dominated by $\bar{f}f \to Va$, scaling as $C\sqrt{s}/f_a$

Chirality-flip operators

one can introduce

$$O_{uH,ij} = \frac{ia}{f_a}(\bar{Q}_i\tilde{H}u_j) \qquad O_{dH,ij} = \frac{ia}{f_a}(\bar{Q}_iHd_j) \qquad O_{eH,ij} = \frac{ia}{f_a}(\bar{L}_iHe_j)$$

⚠ **NOT shift-invariant!** but related to O_f via EOM, e.g.

$$-O_{e,ij} = O_{eH,kj}(Y_e)_{ki} + O^\dagger_{eH,ik}(Y^\dagger_e)_{jk} + \frac{g'^2}{16\pi^2}O_{\tilde{B}}\delta_{ij}$$

$O_f \to O_{fH}$ trading always possible. $O_{fH} \to O_f$ only possible if

Chala, Guedes, Ramos, Santiago 2012.09017

$$C_{eH} = A_eY_e + Y_eB_e \qquad C_{uH} = A_QY_u + Y_uB_u \qquad C_{dH} = A_QY_d + Y_dB_d$$

with $A_f = A_f^T, B_f = B_f^T$.

- ☞ $\{O_{fH}\}$ as above have same # DOFs as $\{O_f\}$
- ☞ trading $O_{\tilde{G}}$ for fermions requires a combination of O_f and O_{fH} (expl. shift break)
- ☞ one can **remove ALL $\mathbf{O_{\tilde{X}}}$** from the basis, but must retain both O_f and O_{fH} terms