# ALP constraints at Colliders

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mostly based on
Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz 1701.05379
Brivio, Éboli, González-García 2106.05977
Bonilla, Brivio, Machado, Trocóniz in preparation

# Defining ALPs

**Axion Like Particles** = pseudo-Goldstone bosons $\leftrightarrow$ approx shift symmetry, derivative couplings

- extremely general, in any model with SSB (QCD axion, Majoron, relaxion...)
- treated conveniently in a EFT Georgi,Kaplan,Randall PLB169B(1986)73

$$\mathcal{L}_{ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{\mathbf{m_a^2}}{2} a^2 - \frac{\mathbf{C_{\tilde{B}}}}{\mathbf{f_a}} B_{\mu\nu}\tilde{B}^{\mu\nu} a - \frac{\mathbf{C_{\tilde{W}}}}{\mathbf{f_a}} W^I_{\mu\nu}\tilde{W}^{I\mu\nu} a - \frac{\mathbf{C_{\tilde{G}}}}{\mathbf{f_a}} G^A_{\mu\nu}\tilde{G}^{A\mu\nu} a + \sum_{f=q,l,u,d,e} \frac{(\mathbf{C_f})_{\mathbf{ij}}}{\mathbf{f_a}} (\bar{f}_i \gamma^\mu f_j)\partial^\mu a \quad (*) \qquad + \mathcal{O}(f_a^{-2})$$

$(*)$ 4 dofs are dependent due to $B$ and $L_i$ conservation

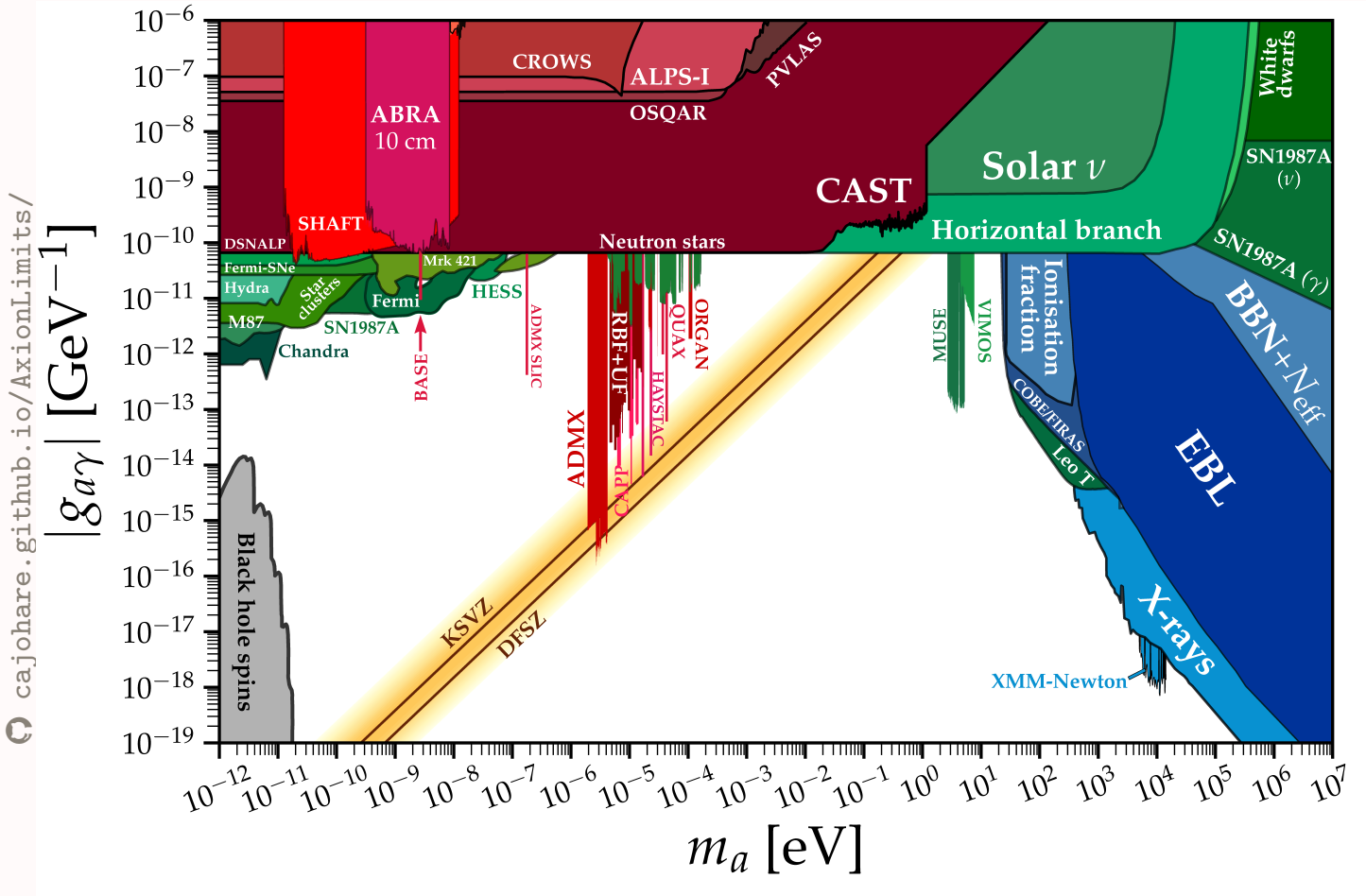
Bauer,Neubert,Renner,Schnubel,Thamm 2110.10698, Bonilla,Brivio,Gavela,Sanz 2107.11392

assuming CP: $\mathbf{29}+m_a$ independent parameters. $\mathbf{14}+m_a$ flavor conserving

$\mathbf{6}+m_a$ with MFV

# A vast phenomenology

- allowed ranges for $m_a$ and $C_i/f_a$ span several orders of magnitude
- natural case where interplay of very different experiments is crucial !



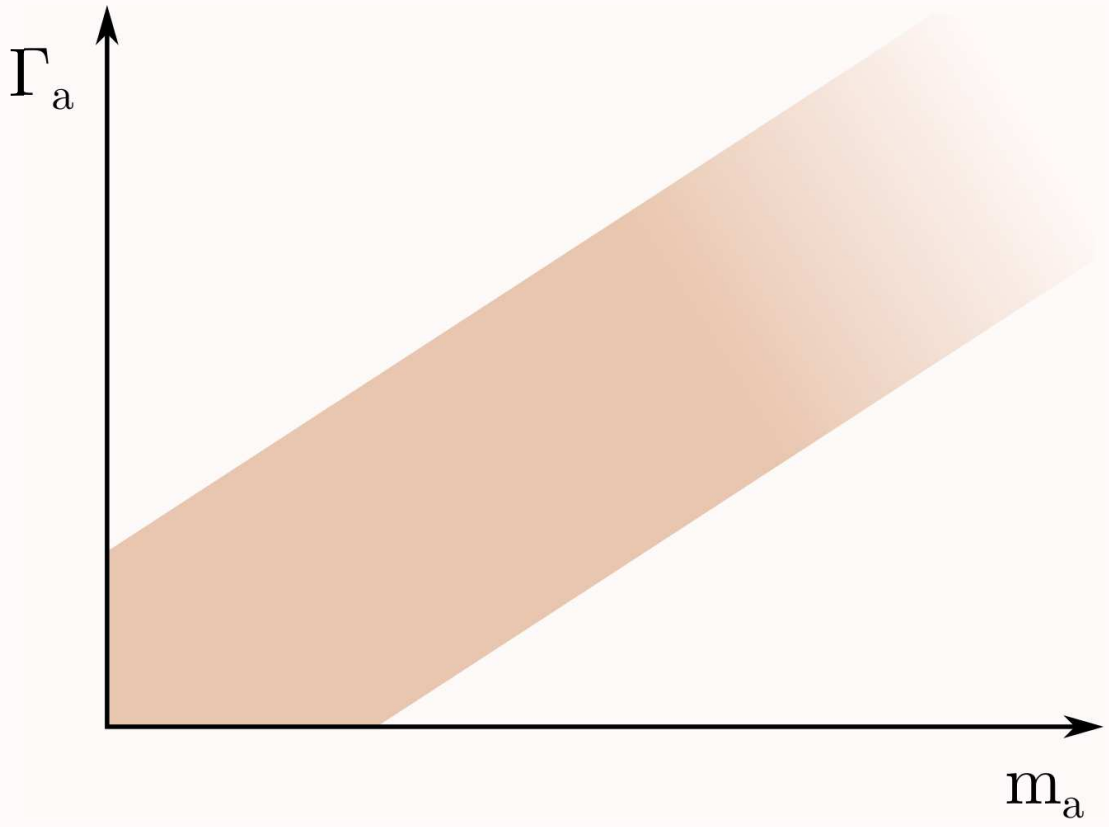
# ALPs at colliders

## 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?

$$\Gamma_a \sim m_a^3 \; (VV)$$
$$\sim m_a \; (f\bar{f})$$



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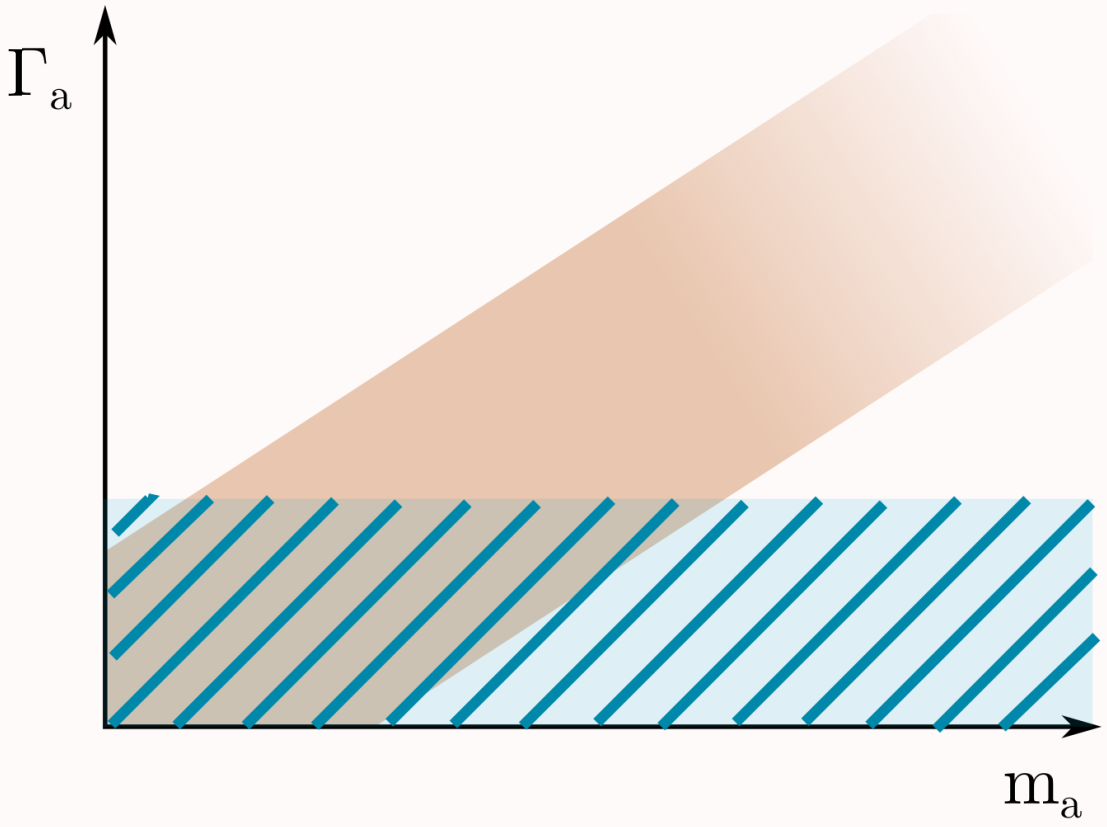


**stable ALP**

$\downarrow$

$\not{E}_T$

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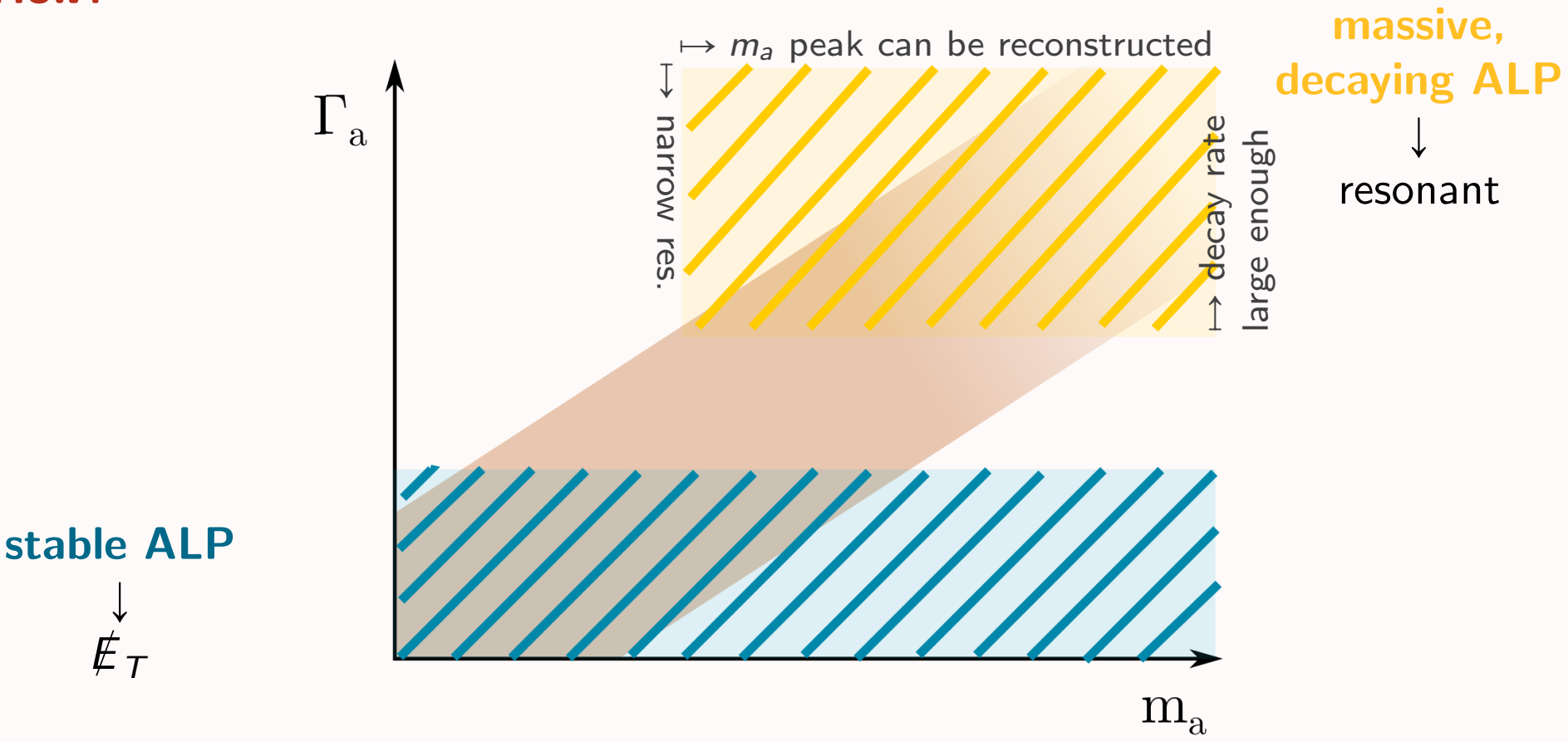

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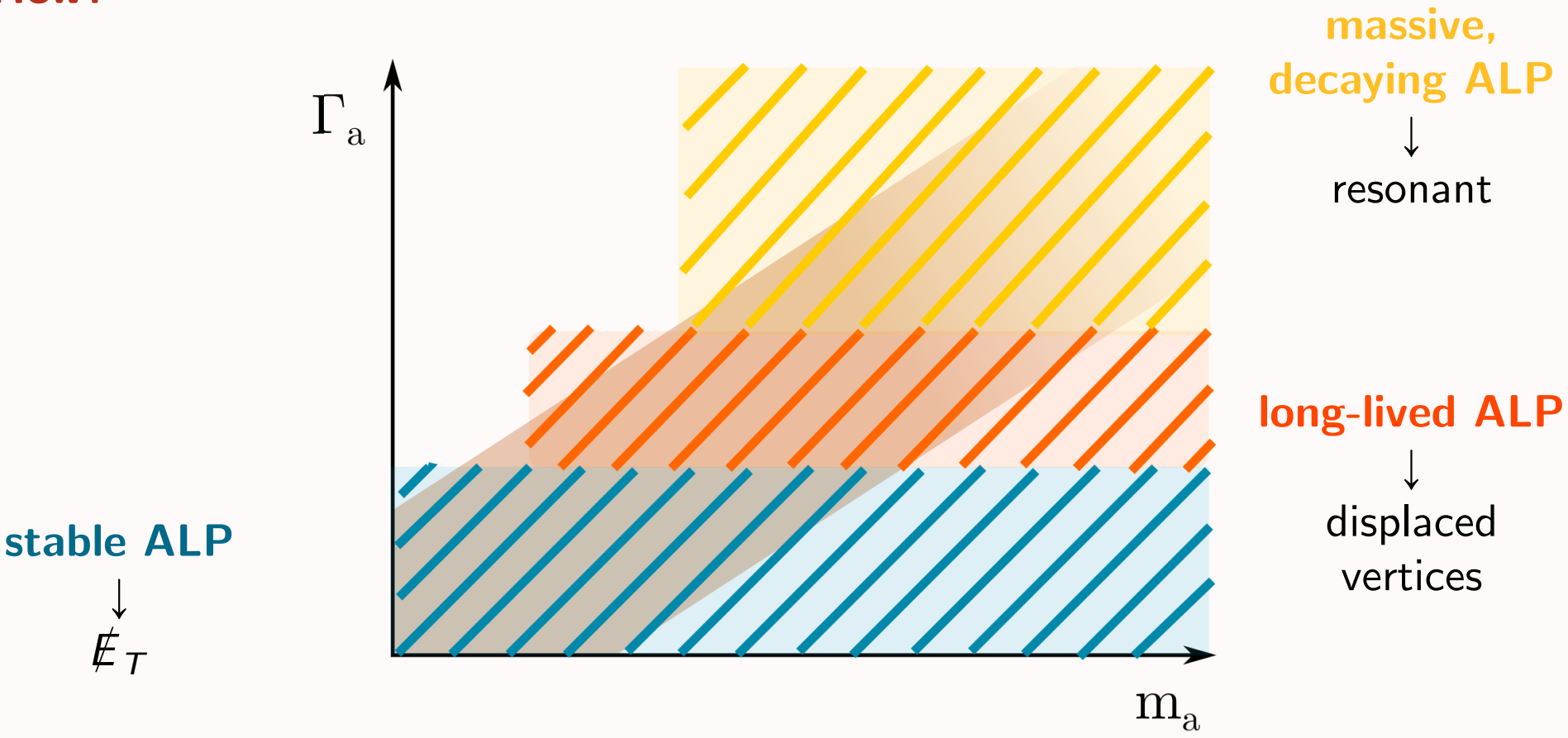

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**off-shell ALP**
↓
non-resonant

**stable ALP**
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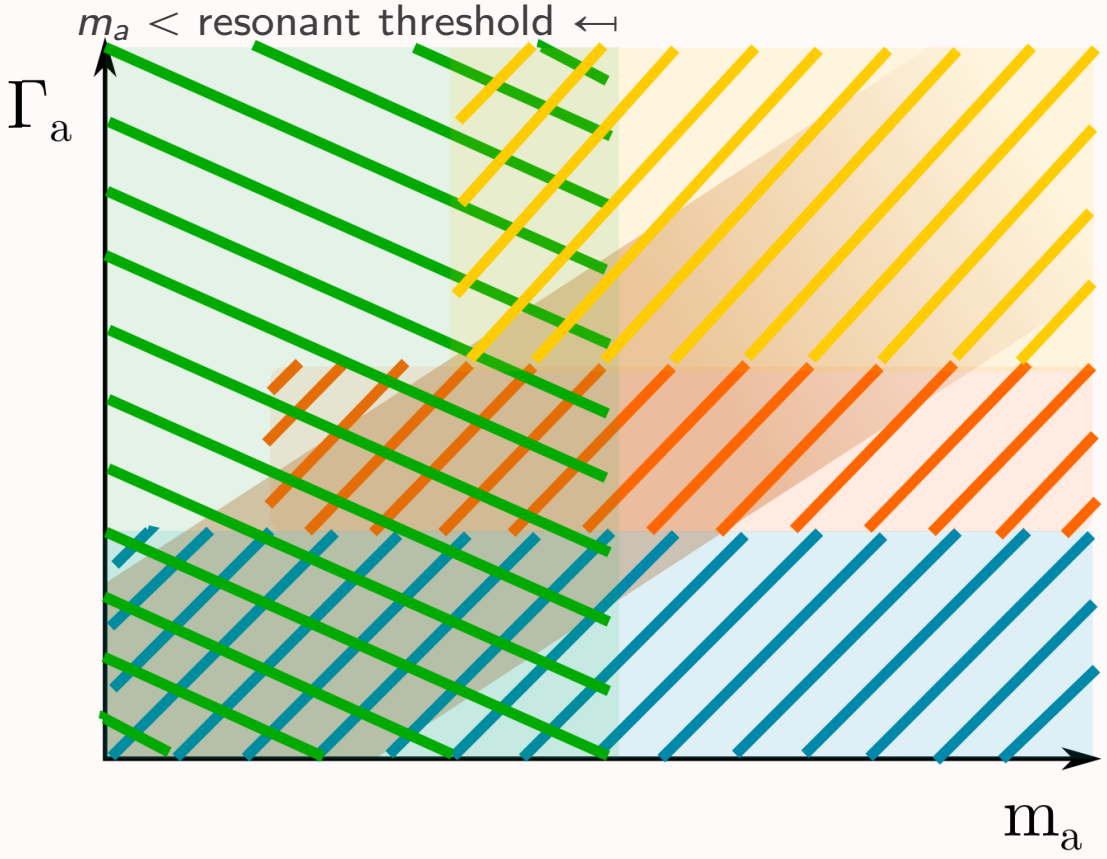
$\not{E}_T$




**massive, decaying ALP**
↓
resonant

**long-lived ALP**
↓
displaced vertices

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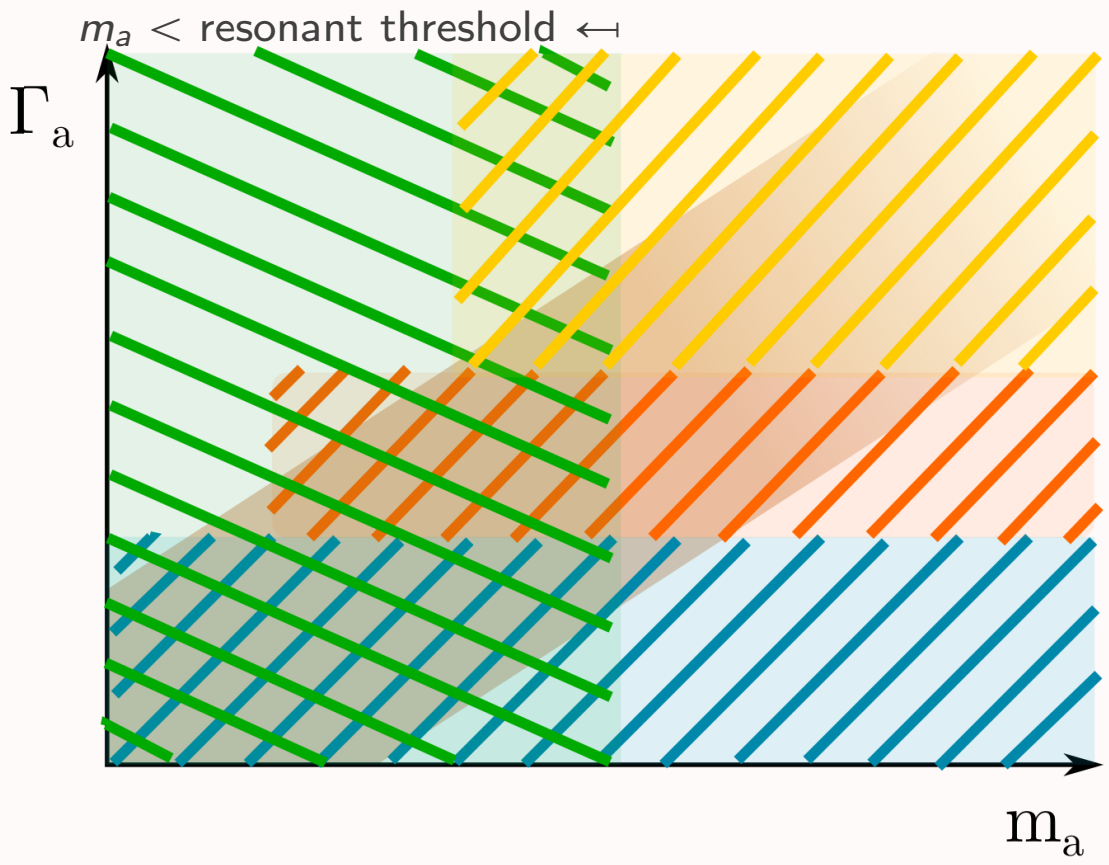


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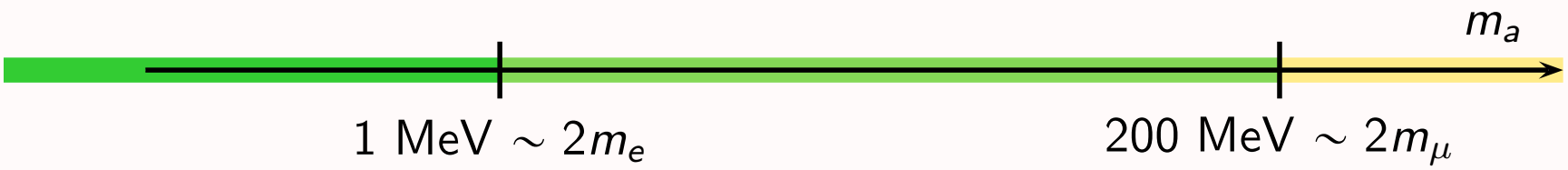
# A stable, invisible ALP

Brivio,Gavela,Merlo,Mimasu,No,delRey,Sanz 1701.05379

**most likely stable** ($c\tau > 10^8\,\mathrm{m}$) **depends on $C_i/f_a$**




- $a \to \gamma\gamma$
  bounded by $g_{a\gamma\gamma} < 10^{-10}$
- $a \to \bar{\nu}\nu\bar{\nu}\nu$ still $\not{E}_T$
- $a \to \gamma\bar{\nu}\nu$
  suppressed $\sim m_a^7/(m_Z^4 f_a^2)$

- $a \to \gamma\gamma$ still bounded
- $a \to ee$
  bounded by $g_{aee} < 10^{-13}$

- $a \to ee$ still constrained
- $a \to \gamma\gamma$ allowed
- $a \to \mu\mu$ allowed
- $a \to$ hadrons allowed
  for $m_a > 3m_\pi \sim 0.5$GeV

$\vdots$

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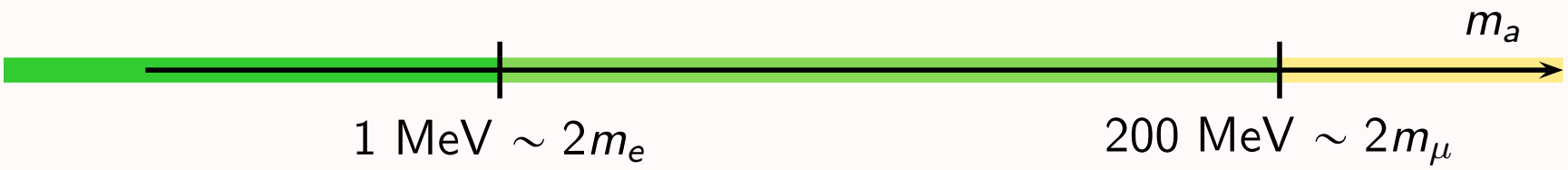


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- $a \to \mu\mu$ allowed
- $a \to$ hadrons allowed for $m_a > 3m_\pi \sim 0.5$GeV

⋮

## constraints from LEP: Z width

Brivio,Gavela,Merlo,Mimasu,No,delRey,Sanz 1701.05379

$\Gamma(Z \to a\gamma) < \Delta\Gamma_Z \simeq 2\,\mathrm{MeV} \to$ $|g_{aZ\gamma}| < 1.8\,\mathrm{TeV}^{-1}$ for $m_a < 90\,\mathrm{GeV}$

$\Gamma(Z \to \gamma + \mathrm{inv}) < 2 \times 10^{-3}\,\mathrm{MeV} \to$ $|g_{aZ\gamma}| < 0.06\,\mathrm{TeV}^{-1}$ for $m_a < 200\,\mathrm{MeV}$

# Constraints from LHC: mono-X

Brivio,Gavela,Merlo,Mimasu,No,delRey,Sanz 1701.05379

[parton level, $C_{\tilde{W}}$ only]

**mono-W** $pp \to l^{\pm} + \not{E}_T$

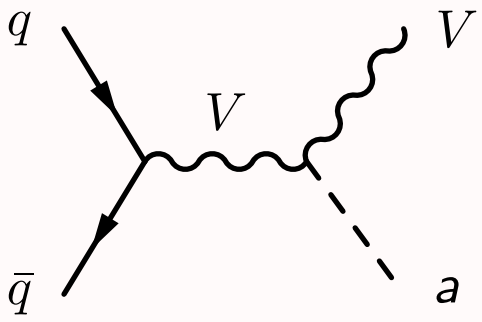
ATLAS 1606.03977 $(\mu)$ $|C_{\tilde{W}}|/f_a < 0.6\,\mathrm{TeV}^{-1}$

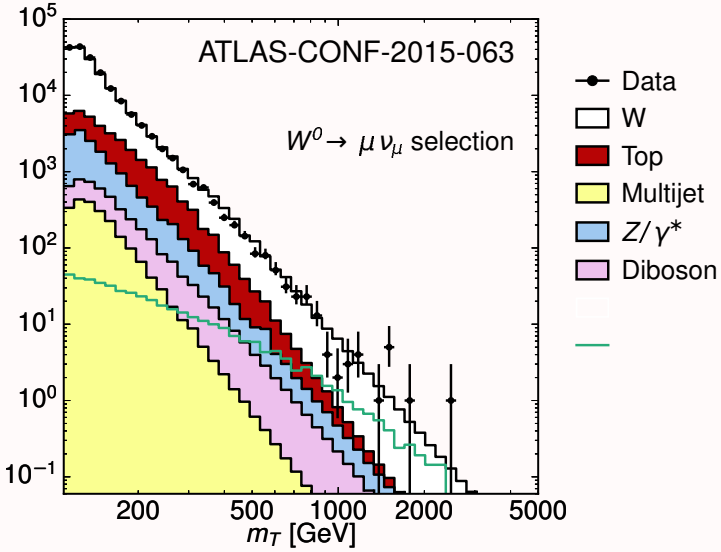
3000 $\mathrm{fb}^{-1}$ $|C_{\tilde{W}}|/f_a < 0.45\,\mathrm{TeV}^{-1}$

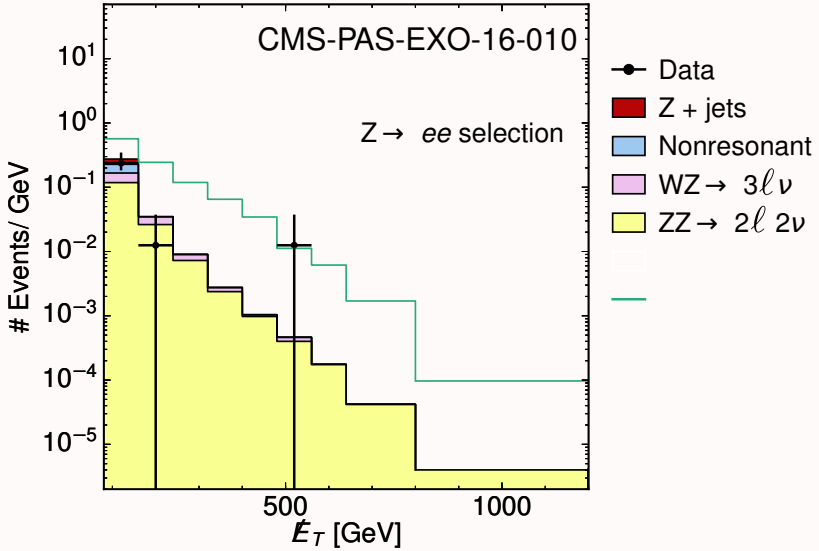
**mono-Z** $pp \to l^+ l^- + \not{E}_T$

CMS 1701.02042 $(e)$ $|C_{\tilde{W}}|/f_a < 0.26\,\mathrm{TeV}^{-1}$

3000 $\mathrm{fb}^{-1}$ $|C_{\tilde{W}}|/f_a < 0.06\,\mathrm{TeV}^{-1}$



# A comment on Higgs constraints

ALP-Higgs couplings are absent at $d = 5$ $\rightarrow$ higher orders

or LO in non-linear EFT: $H \rightarrow \frac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \; \mathbf{U} = \exp\left( i \frac{\pi^I \sigma^I}{v} \right)$

| | linear EFT | non-linear EFT |
|---|---|---|
| $ahZ$ | $(\partial^\mu a)(H^\dagger i \overleftrightarrow{D}_\mu H)(H^\dagger H)$ | $i(\partial^\mu a)\,\mathrm{Tr}(\mathbf{U}^\dagger D_\mu \mathbf{U} \sigma^3) h$ |
| $haa$ | $(\partial_\mu a \partial^\mu a)(H^\dagger H)$ | $(\partial_\mu a \partial^\mu a) h$ |

mainly probed in Higgs decays

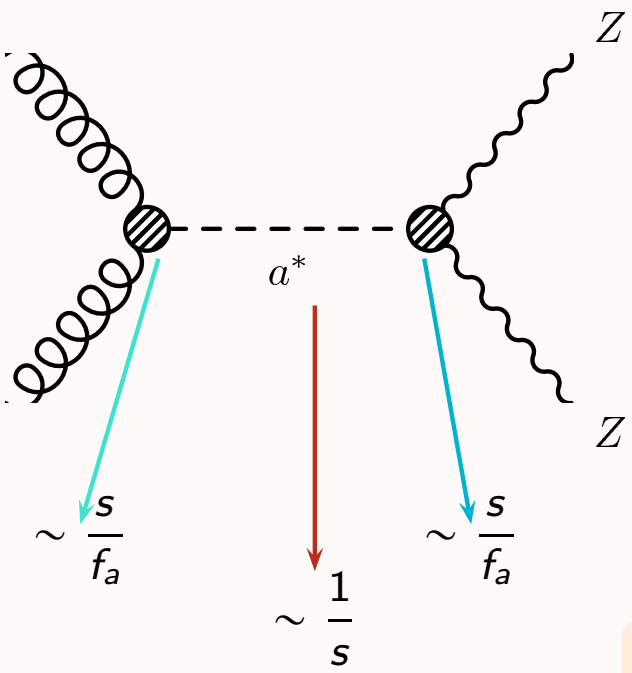
also: Bauer,Neubert,Thamm 1708.00443

- $\mathrm{Br}(h \rightarrow aZ) < \mathrm{Br}(h \rightarrow \mathrm{BSM}) < 0.15$ ATLAS-CONF-2021-053
  $\mathrm{Br}(h \rightarrow a\bar{\nu}\nu) < \mathrm{Br}(h \rightarrow \mathrm{inv.}) < 0.14$
- $\mathrm{Br}(h \rightarrow aa) < \mathrm{Br}(h \rightarrow \mathrm{inv})$
- mono-$h$ also possible but weaker

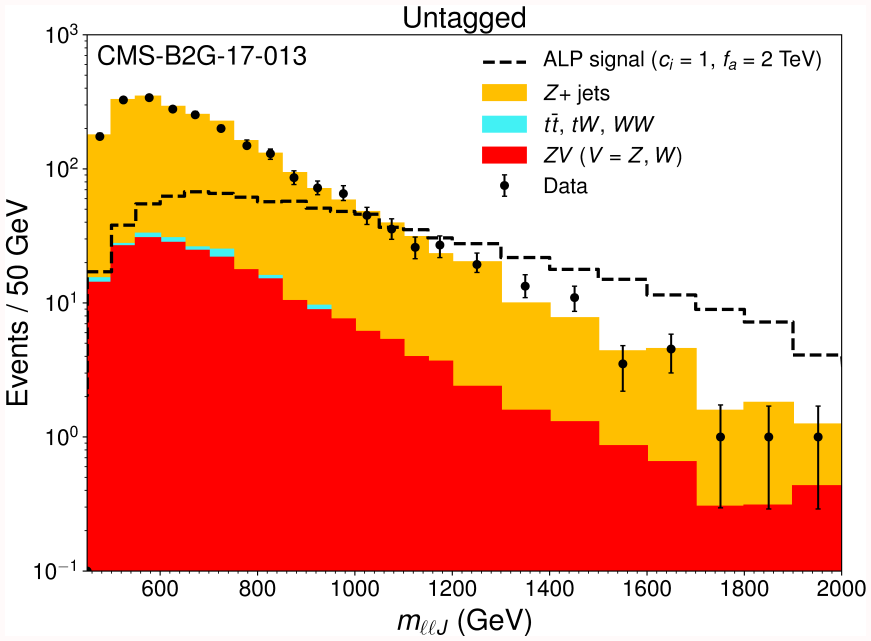
# New: Non-resonant searches

$ZZ$, $\gamma\gamma$, $t\bar{t}$: 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 $m_a < \sqrt{s} \leqslant 2m_Z$




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




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

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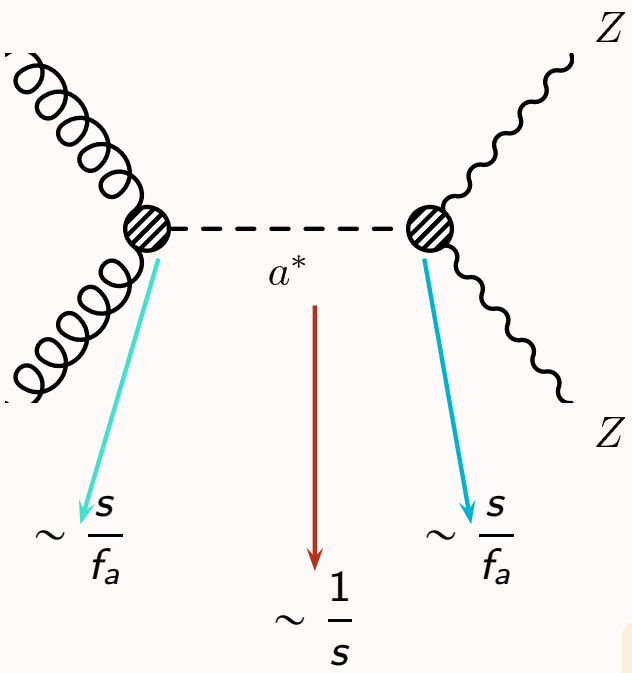


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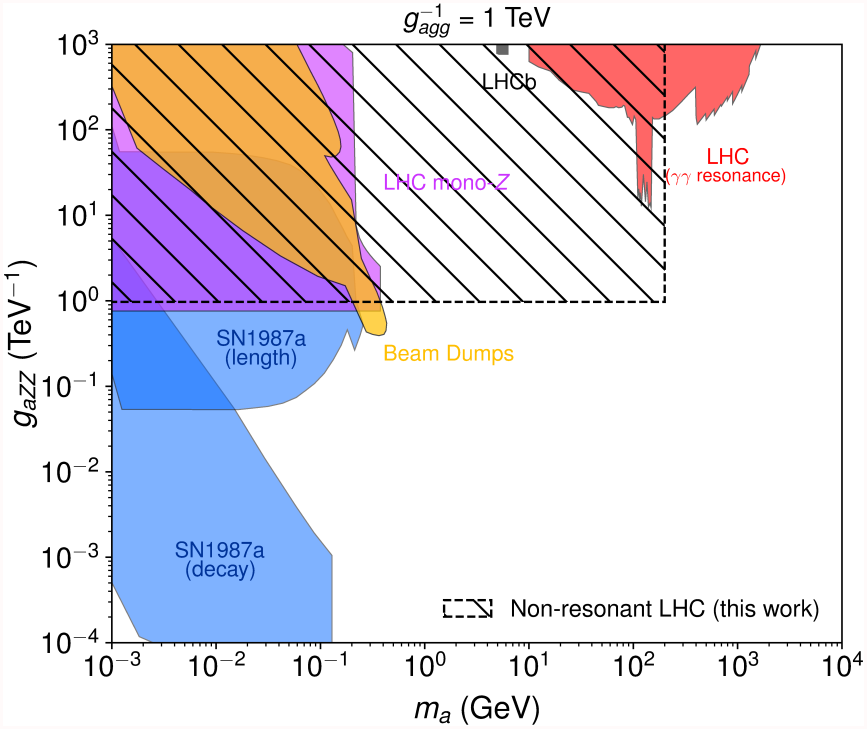


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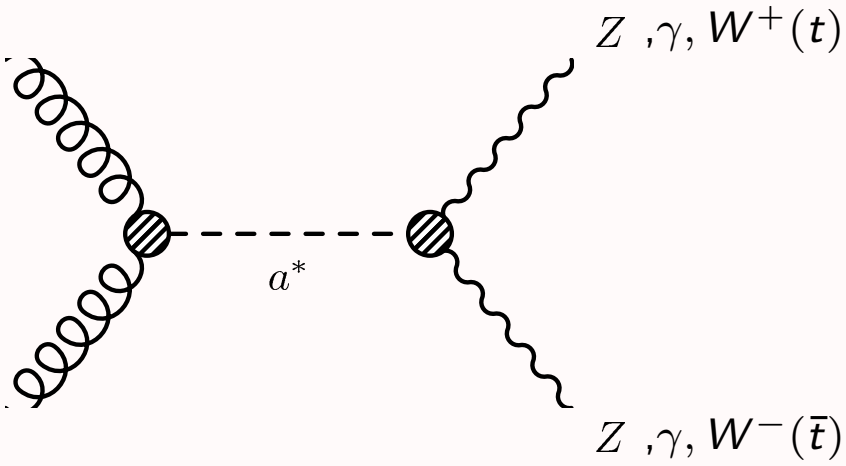
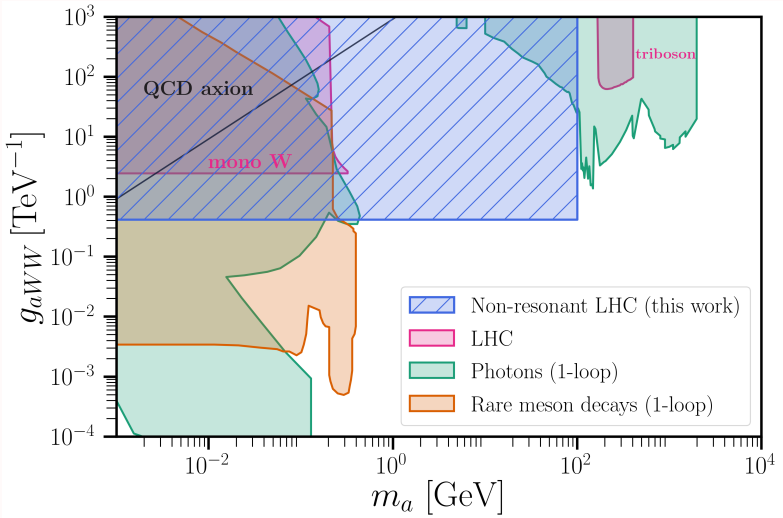
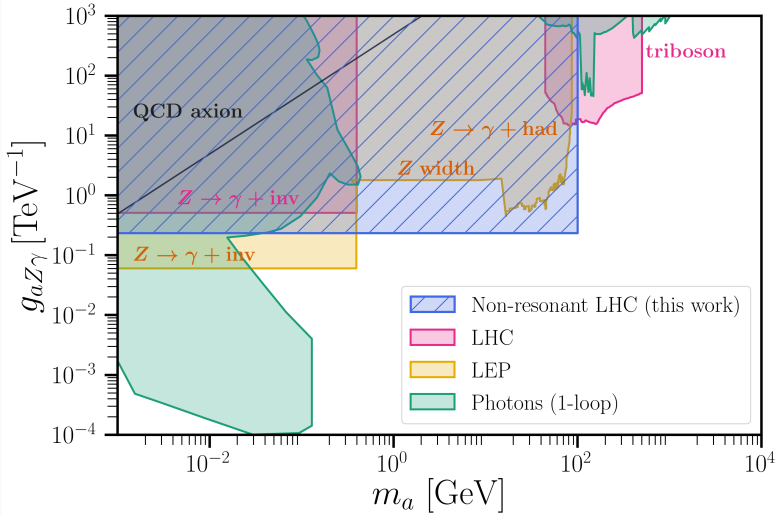



⚠ bound scales with $1/g_{aGG} \neq 0$

here normalized to $g_{aGG} = \dfrac{C_{\tilde{G}}}{f_a} = 1\,\mathrm{TeV}^{-1}$

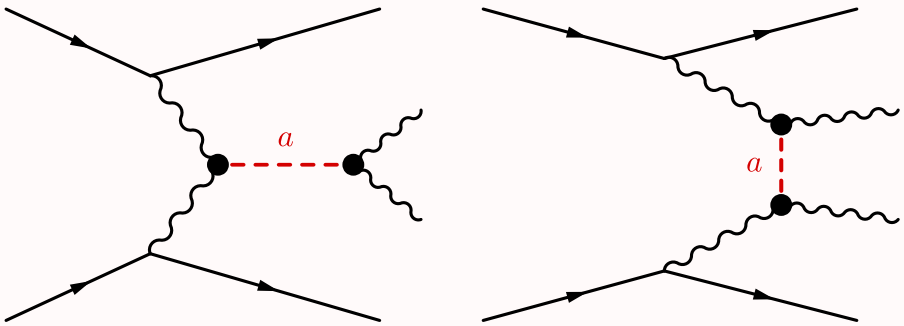
# Non-resonant searches in VBS

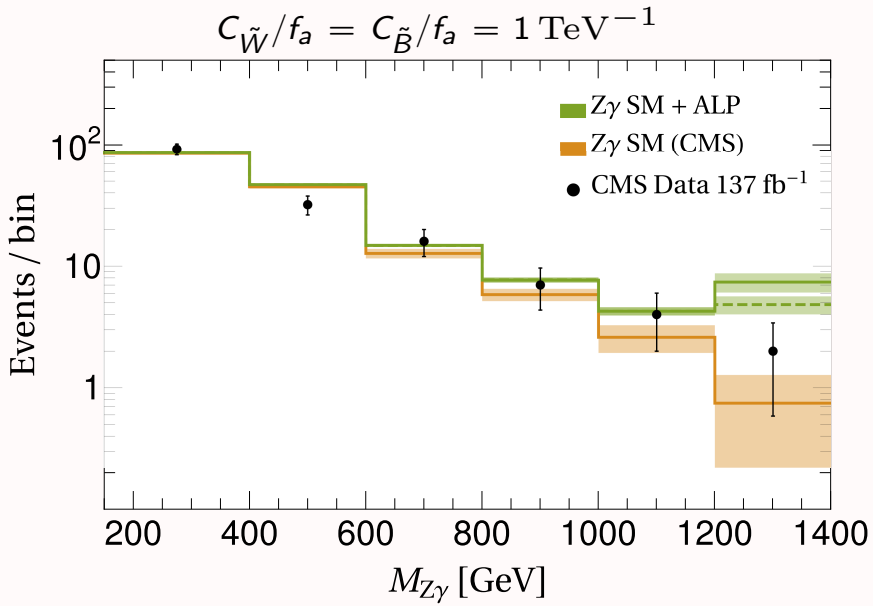
Bonilla,Brivio,Machado,Troconiz in preparation

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: $W^\pm W^\pm, W^\pm Z, W^\pm\gamma, Z\gamma, ZZ$




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

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

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

# Unitarity constraints

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

Brivio, Éboli, González-García
2106.05977

minimal EFT self-consistency ↔ preservation of perturbative unitarity

⚠ partial-wave unitarity defined for elastic scattering!

→ diagonalize the matrix of all possible $2 \to 2$ scatterings
& impose unitarity on eigenvalues

only leading dependence in $s$. omit $Va \to Va$, for which the $d = 6$ operator is relevant

**VV→ VV**

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

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

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**VV→ Va**

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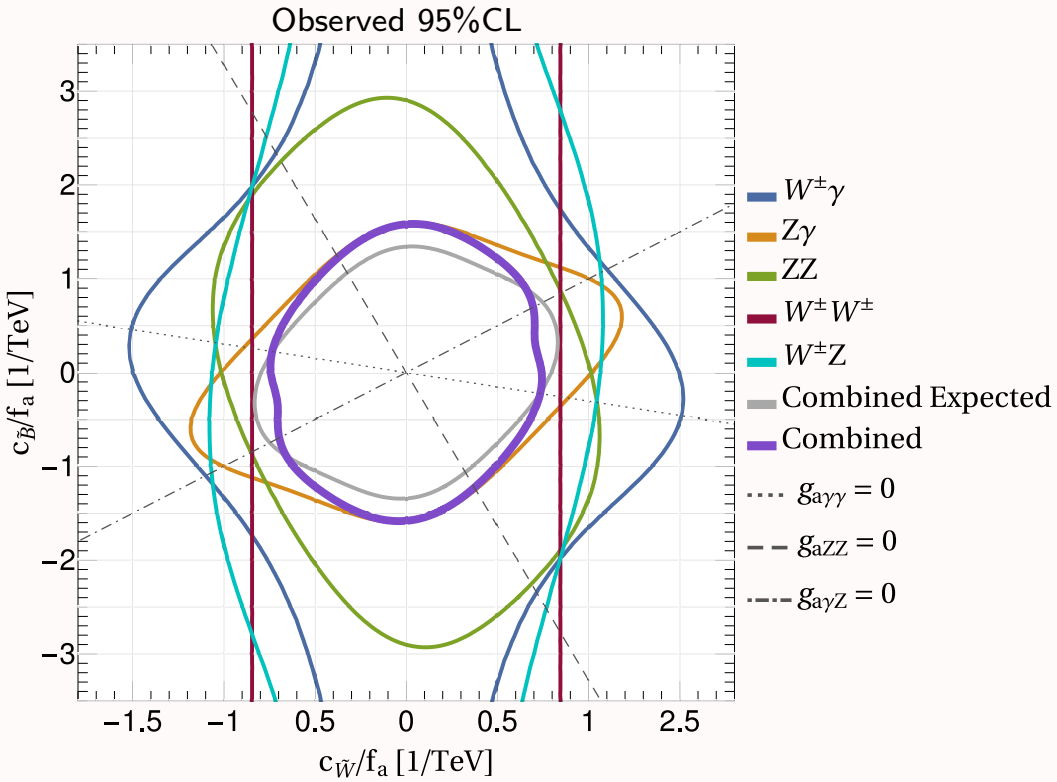
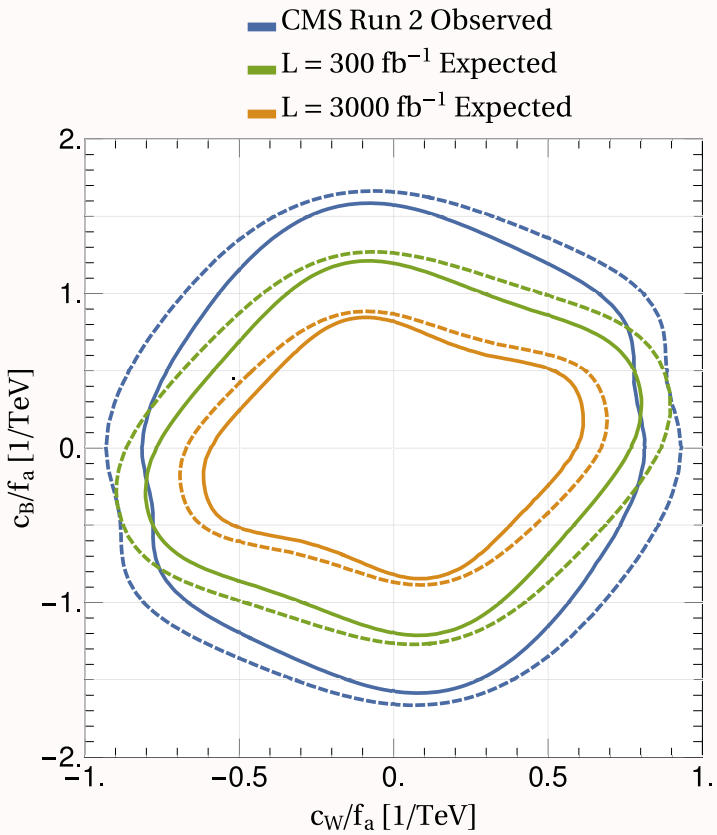
$< 1$ event beyond the unitarity bound for all VBS channels & lumis, with $C_i/f_a$ at 95%CL boundary → **safe**

# Non-resonant searches in VBS: results

gauge invariant param. → all EW couplings simultaneously accounted for

PRELIMINARY




projections

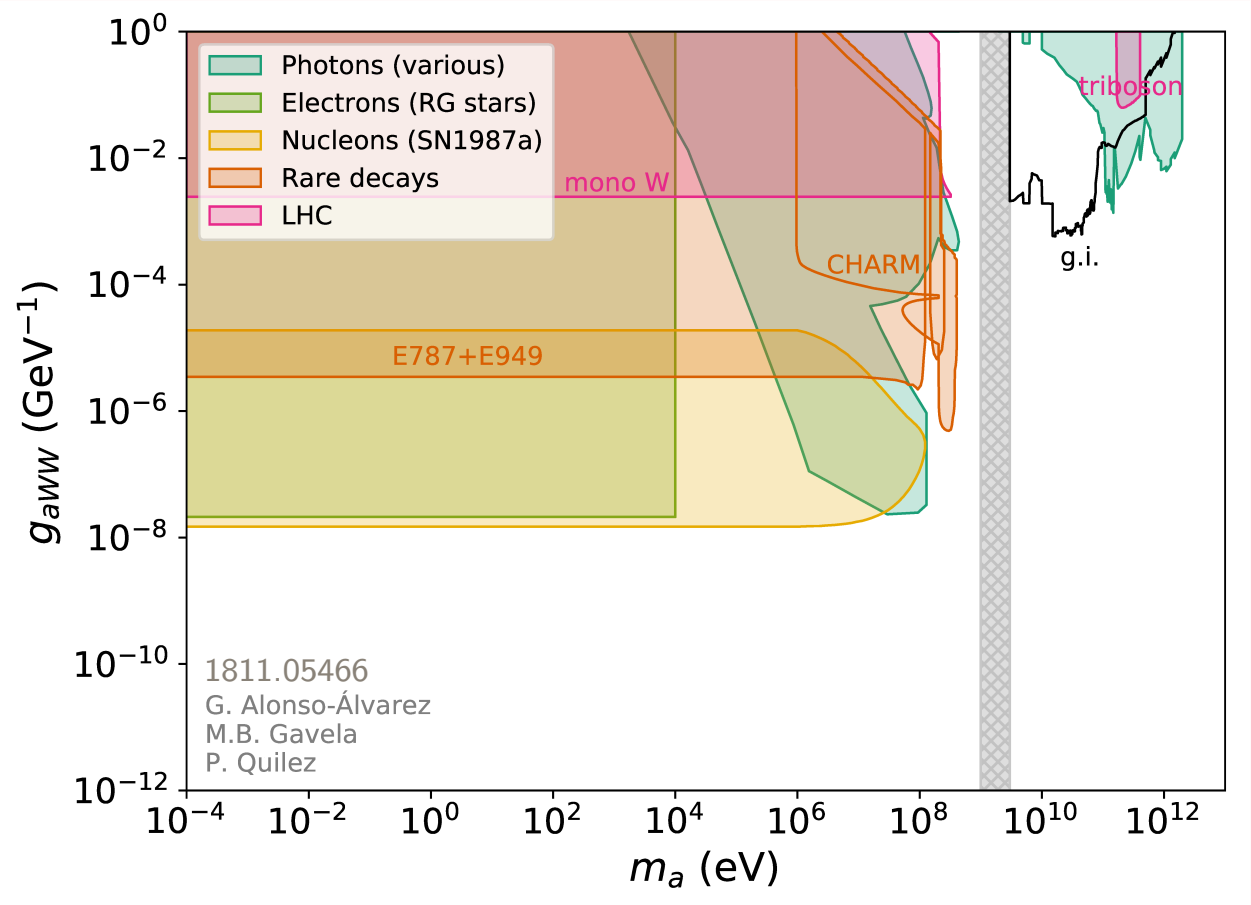
dashed = with $\sqrt{\hat{s}} \leqslant 2\,\mathrm{TeV}$

# 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



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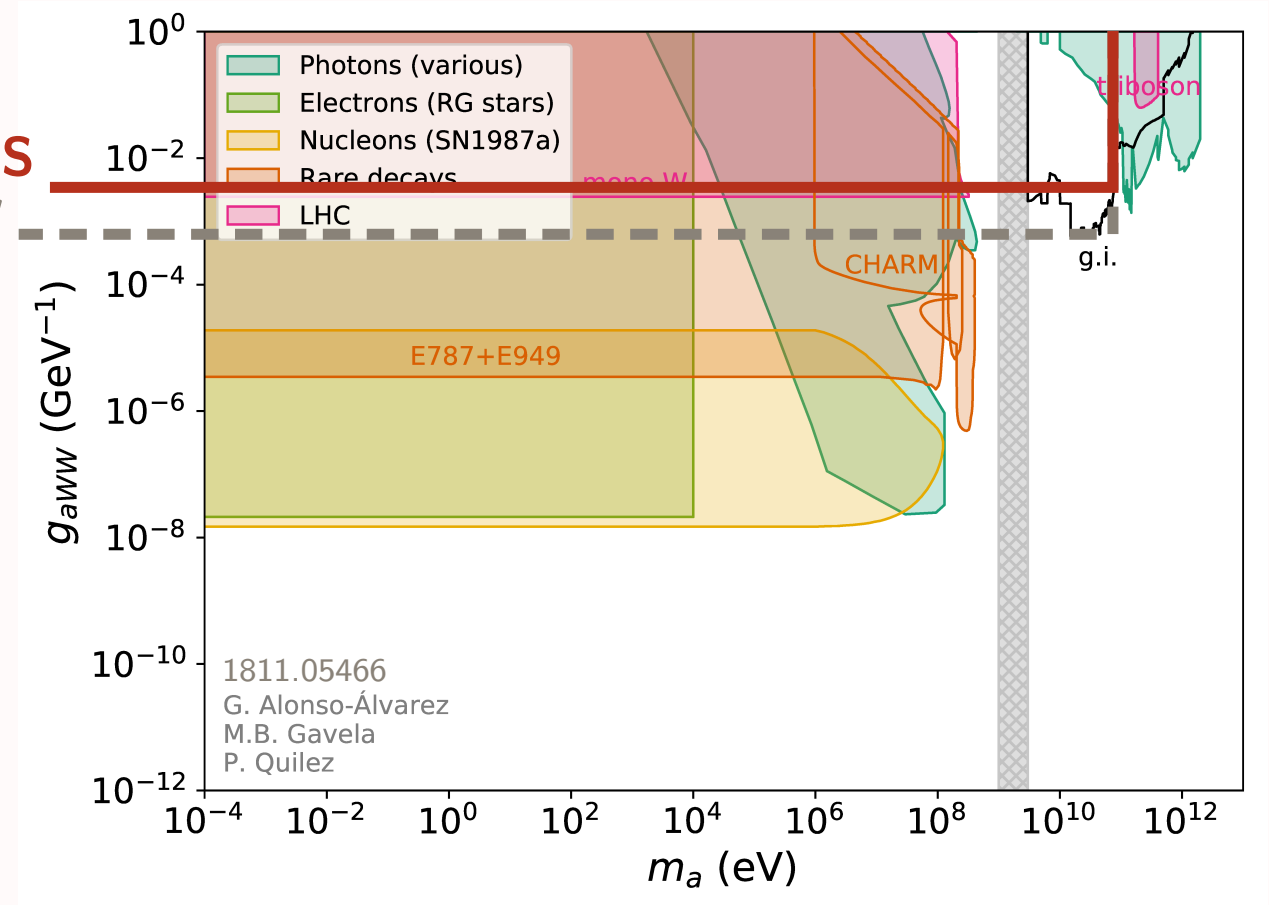
non-res. VBS

non-res. WW



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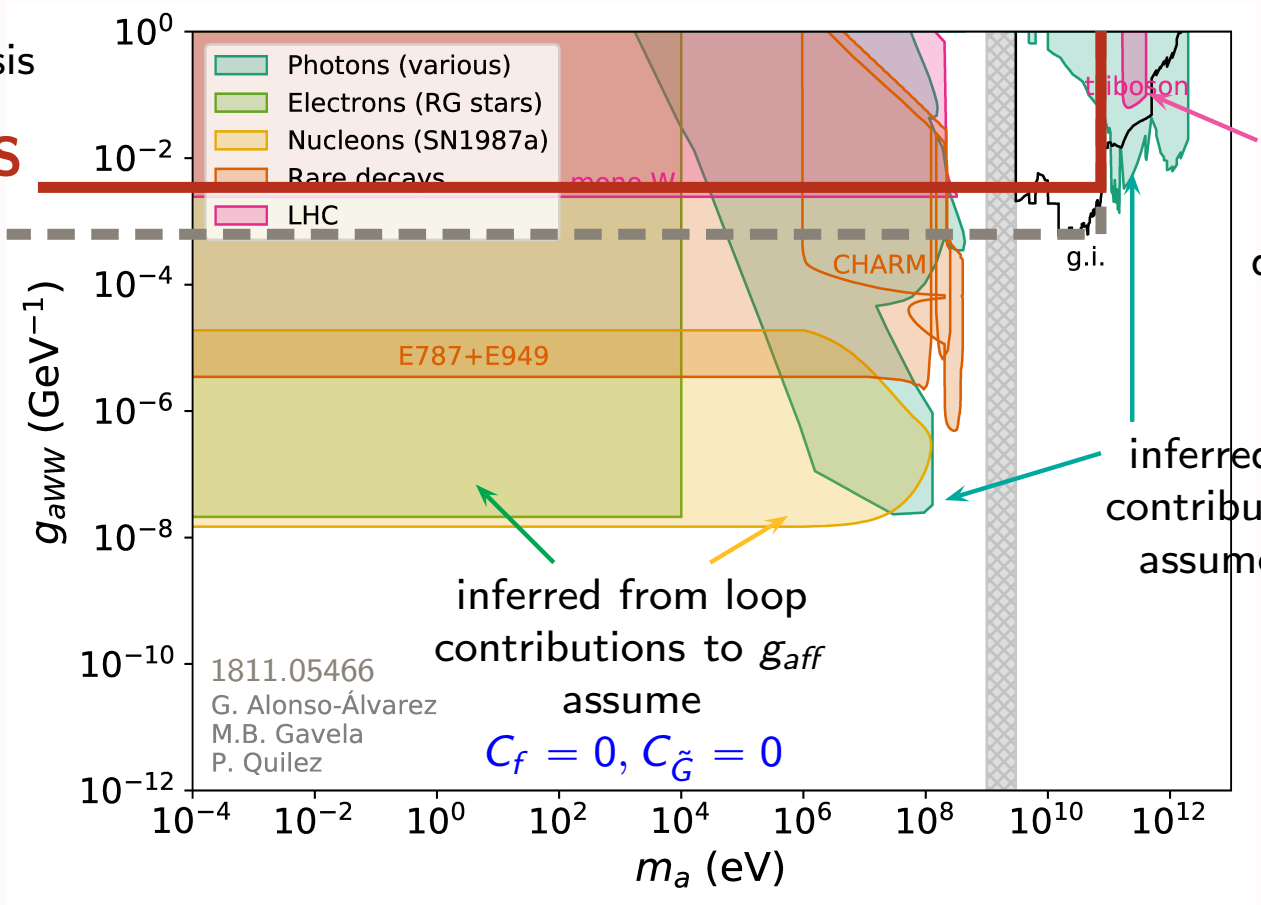
} relevant to break flat directions

projected from gauge inv. analysis
↓
**non-res. VBS**
**non-res. WW**
↑
scales with $C_{\tilde{G}}$




inferred from loop contributions to $g_{aff}$ assume $C_f = 0, C_{\tilde{G}} = 0$

inferred from loop contribution to $g_{a\gamma\gamma}$ assume $g^0_{a\gamma\gamma} = 0$

resonant ALP $\rightarrow \propto 1/\Gamma_a$ depends on all $C_i$

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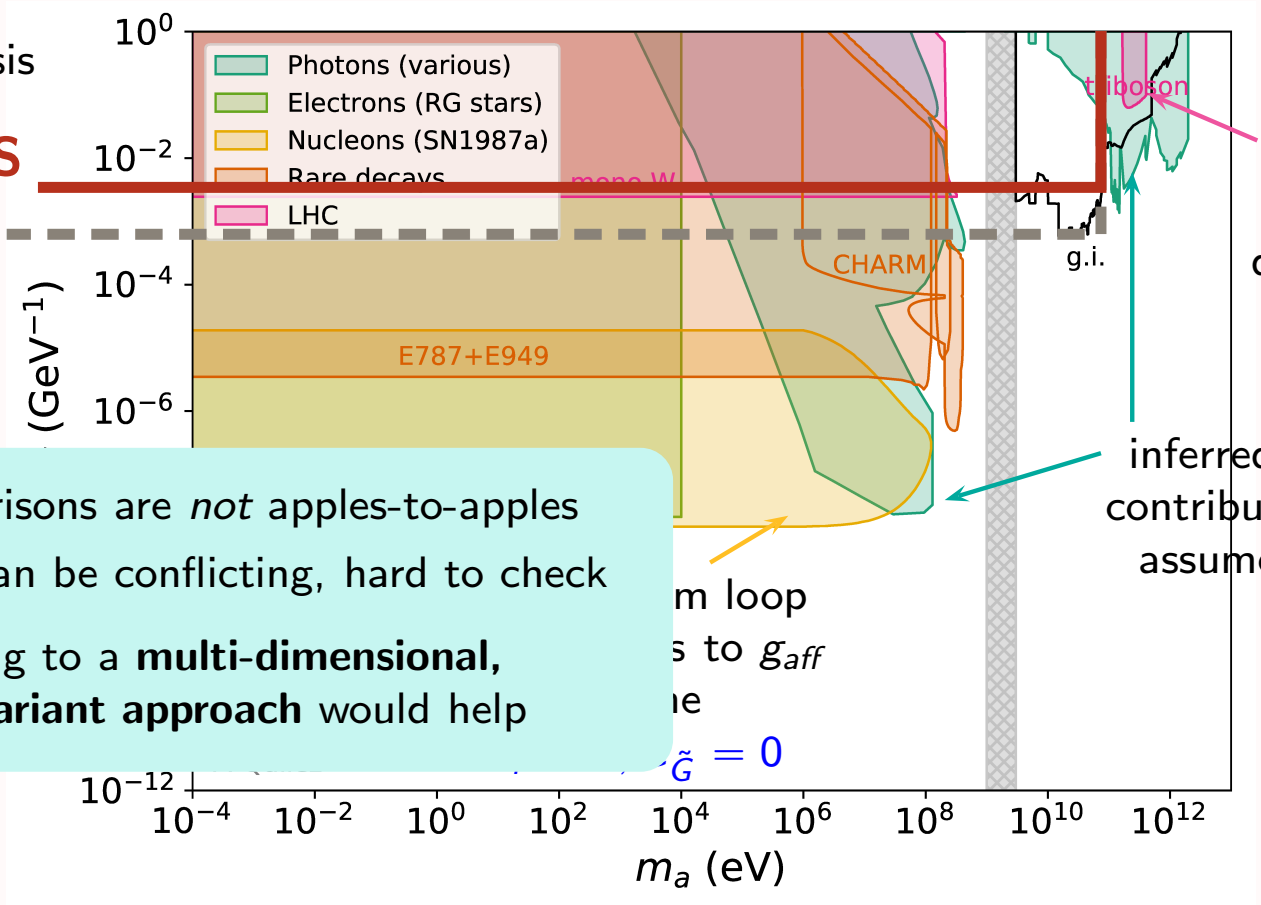



resonant ALP
$\rightarrow \propto 1/\Gamma_a$
depends on all $C_i$

inferred from loop contribution to $g_{a\gamma\gamma}$
assume $g^0_{a\gamma\gamma} = 0$

m loop
s to $g_{aff}$
ne
$_{\tilde{G}} = 0$

often comparisons are *not* apples-to-apples
assumptions can be conflicting, hard to check

→ moving to a **multi-dimensional, gauge-invariant approach** would help

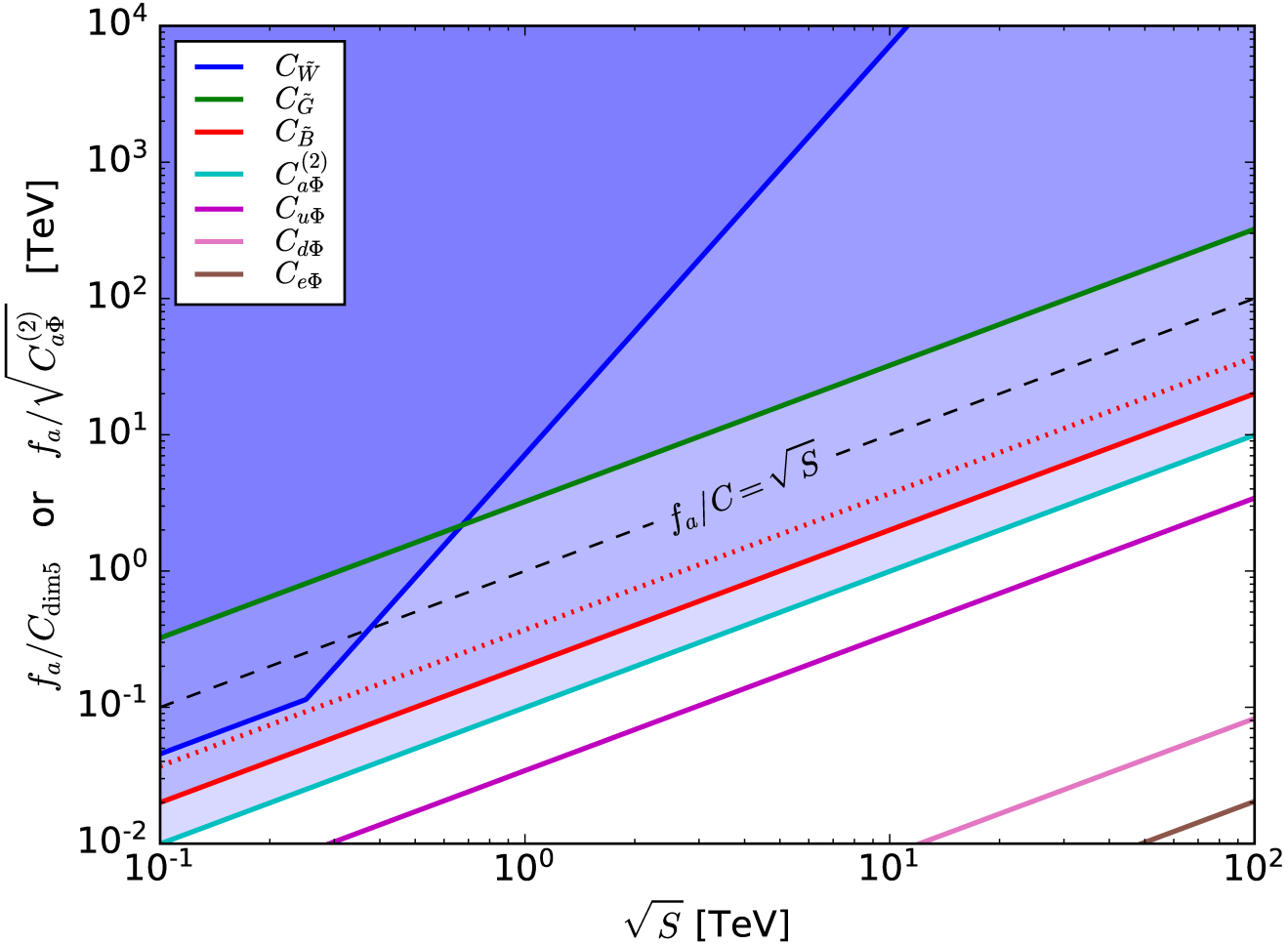
# Summary

- ALPs are very general and have a uniquely rich phenomenology
- important case study for this workshop (literally table-top to collider)
- **collider pheno** depends on $m_a$ and $\Gamma_a$
  - ALP as MET (mono-X, $Z/h$ decays)
  - ALP as a LLP (displaced vertices)
  - ALP as a resonance ($a \to \gamma\gamma, \bar{f}f, Z\gamma \ldots$)
  - ALP as off-shell mediator (non-resonant effects)
- worth working towards a global approach ("easy" EFT)

# Backup slides

# ALP unitarity bounds

Brivio, Éboli, González-García 2106.05977



# Constraints from LHC: $aW\gamma$

$pp \to aW^{\pm}\gamma$ can help disentangling operators in non-linear setup