Axions and other light states

HEP probes

Axions++ (Annecy, 2023)

Veronica Sanz (Valencia)

VNIVERSITAT DE VALÈNCIA

Axions and other pseudo-GBs in a nutshell

approx global symmetry
+
strong dynamics (spontaneous breaking)
—> **pseudo-GBs**

Examples

light quark chiral symmetry + QCD confinement
—> **pions/kaons in QCD**
Peccei-Quinn+ strong dynamics
—> **QCD axion**
new fermions chiral symm+new strong dyn@EW scale
—> **composite Higgs**
XDIM translation invariance + compactification
—> **radion**
scale invariance + strong dynamics
—> **dilaton…**
and many others, like the **gravitino**

Axions and other pseudo-GBs in a nutshell

Result: a scalar dof with shift symmetry

$$a \to a + C$$

non-linearly, from phase invariance e^{ia/f_a}

where scale fa associated with strong dynamics/ compactification

Shift symmetry would forbid a d=4 potential (mass/self-interactios)

Axions and other pseudo-GBs in a nutshell

Result: a scalar dof with shift symmetry

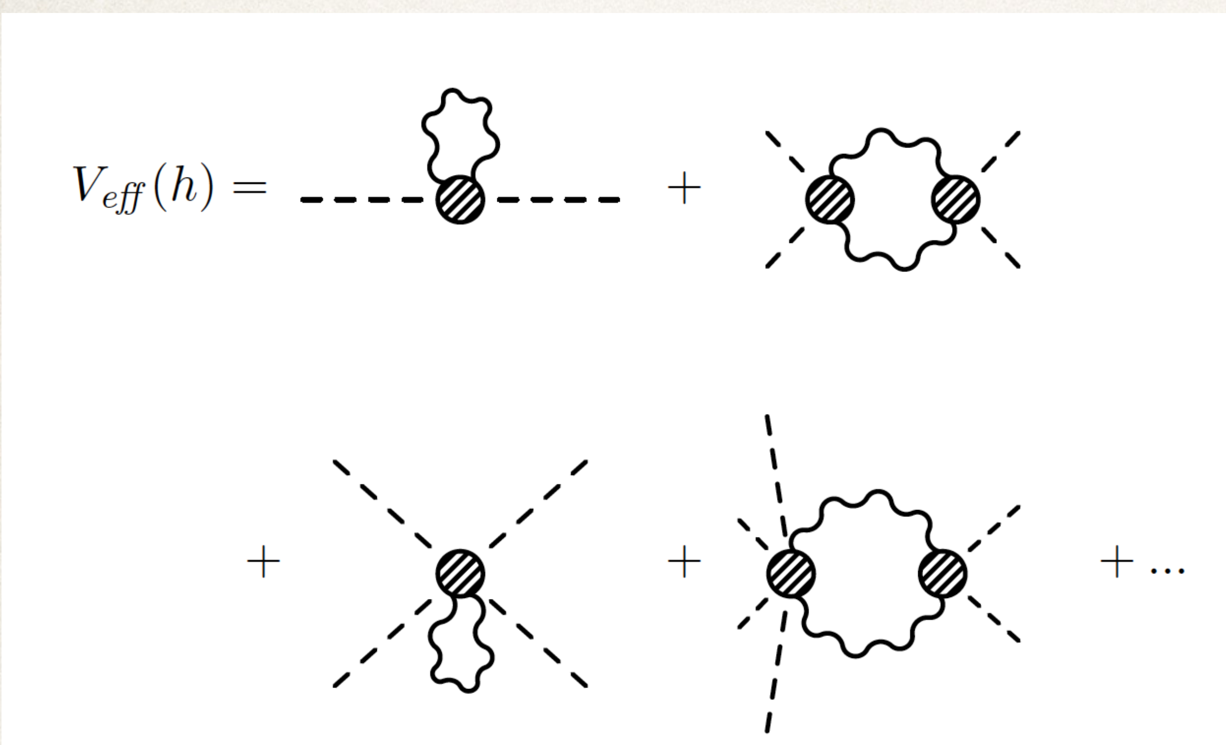
$$a \to a + C$$

non-linearly, from phase invariance e^{ia/f_a}

where scale fa associated with strong dynamics/ compactification

Shift symmetry would forbid a d=4 potential (mass/self-interactios)

Potential: can be generated with explicit breaking, eg. *Composite Higgs*



$$\Sigma(x) = \exp(i\sqrt{2}h^a(x)X^a/f)\Sigma_0$$

à la Coleman-Weinberg

gauge $\Pi_1(p^2)\Sigma^T A_\mu A_\nu \Sigma$

yukawa $\overline{\Psi}\Gamma^i\Sigma_i\Psi$

Axions and other pseudo-GBs in a nutshell

Result: a scalar dof with shift symmetry

$$a \to a + C$$

non-linearly, from phase invariance e^{ia/f_a}

where scale fa associated with strong dynamics/ compactification

Shift symmetry would forbid a d=4 potential (mass/self-interactios)

Interactions: can be generated at d=5 and higher

$$\mathcal{L} \supset \frac{c_i}{f_a} (\partial_\mu a) \mathcal{O}^\mu_{SM}$$ indep. of explicit breaking

e.g. coupling to fermions proportional to mass

These interactions are the way we look for the light states

What HEP colliders can do

The LHC collides **protons**, made of quarks and gluons
Colliders can efficiently probe the coupling to
-photons
-gluons
-massive EW bosons
-tops
Other light fermions are mass suppressed,
so lepton colliders use the same probes

In the eV-MeV mass range, other probes are **more powerful**
but even there, colliders are a **xcheck**

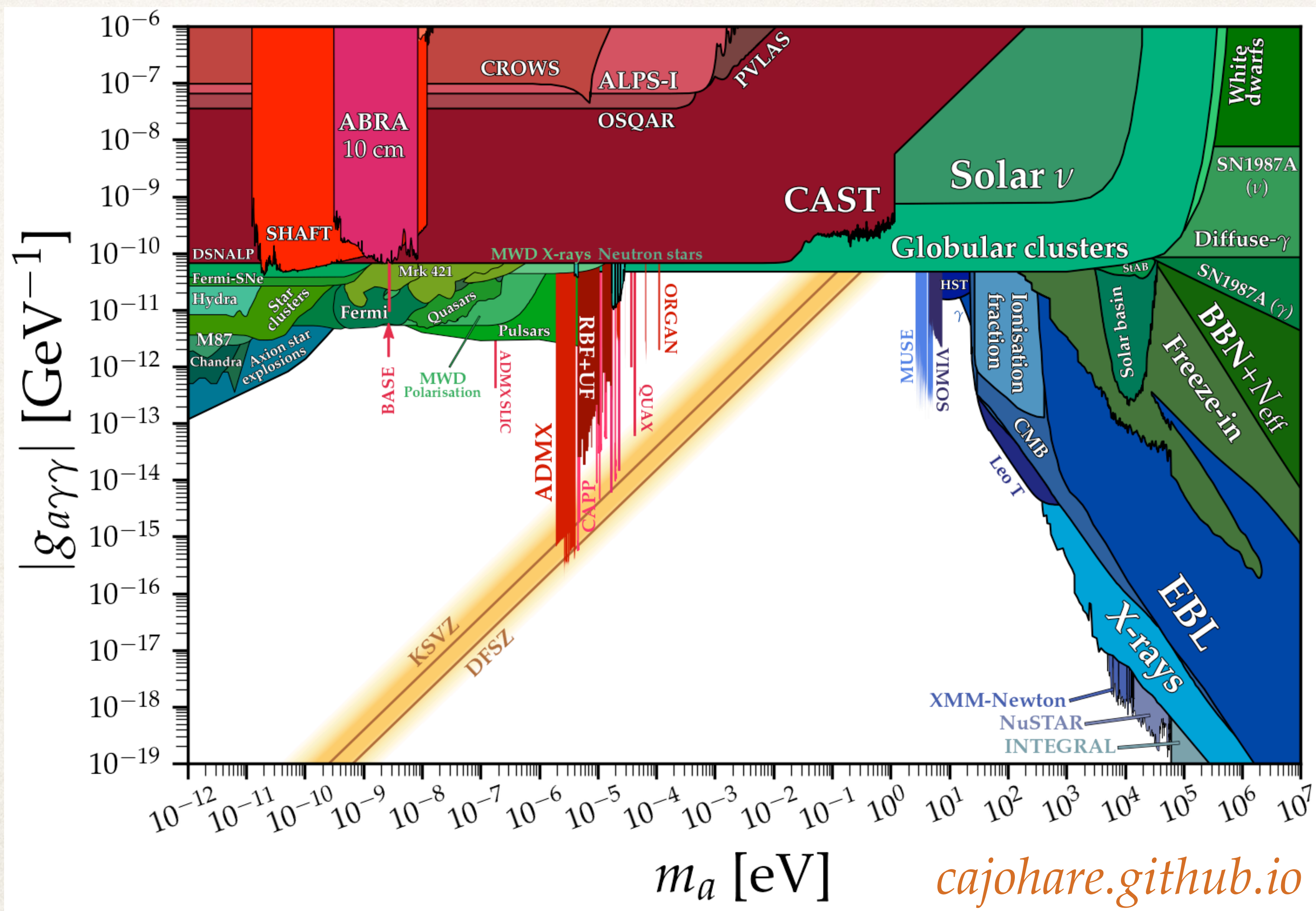
Coupling to photons and gluons

Archetypical ALP

A lot of the studies on ALPs are motivated by
the QCD axion and extensions

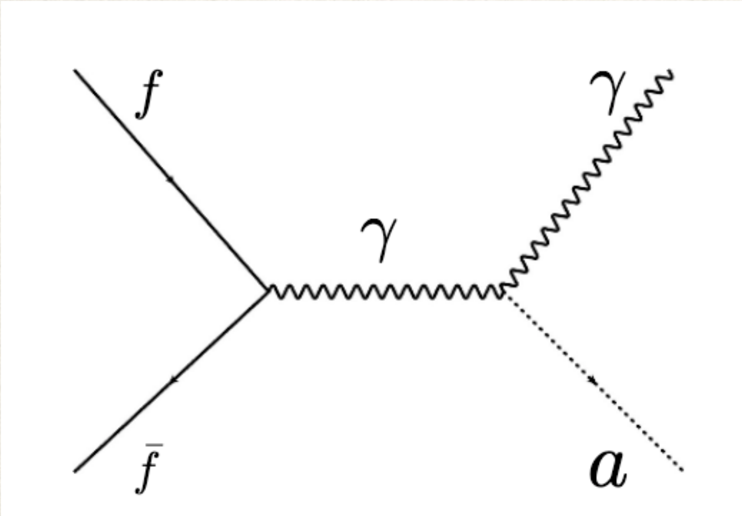
$$\mathcal{L} \supset \frac{c_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

assumes ALP is a very light CP-odd scalar coupled to photons

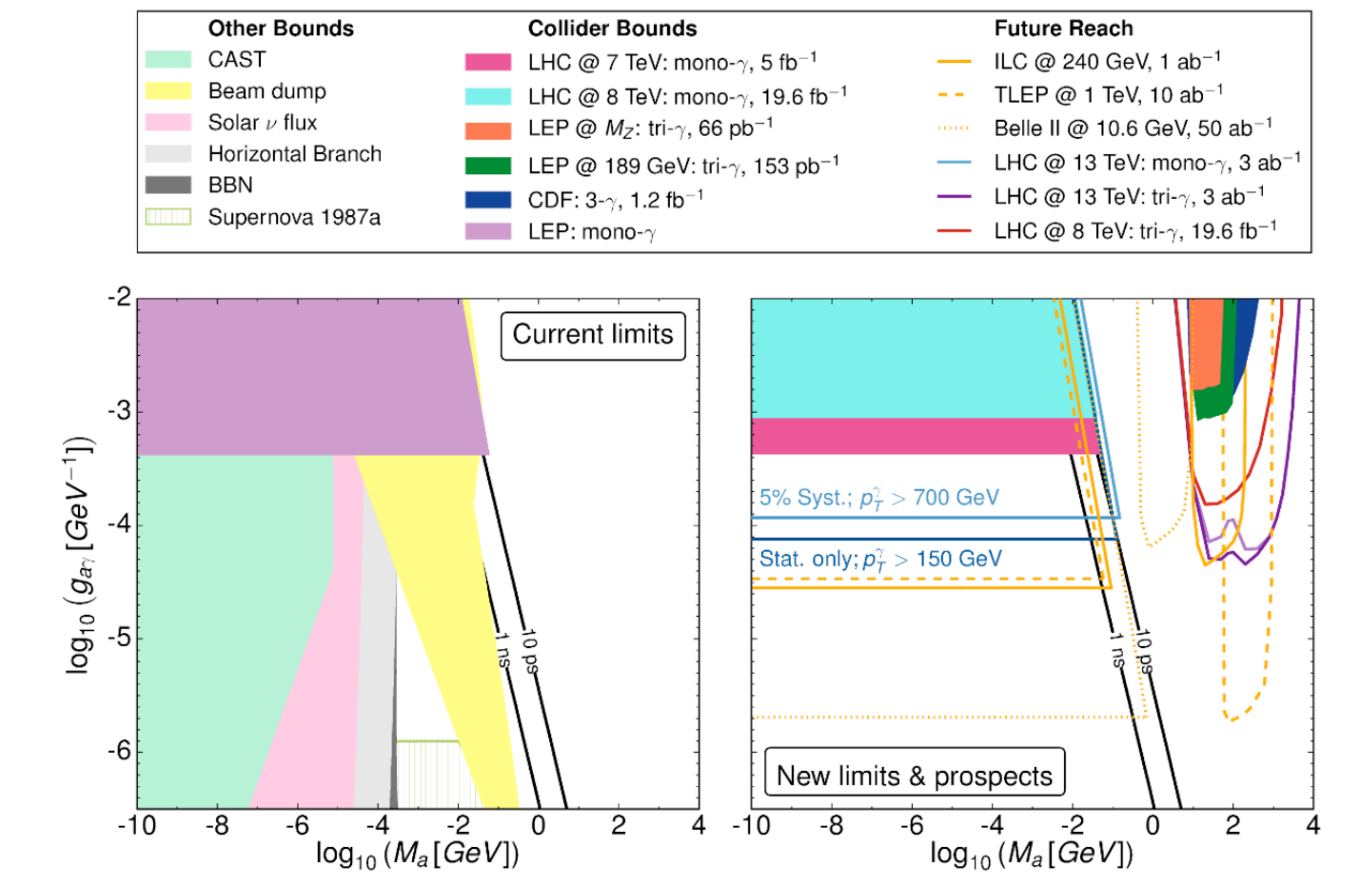


ALPs at colliders

Mimasu, VS. JHEP (15)

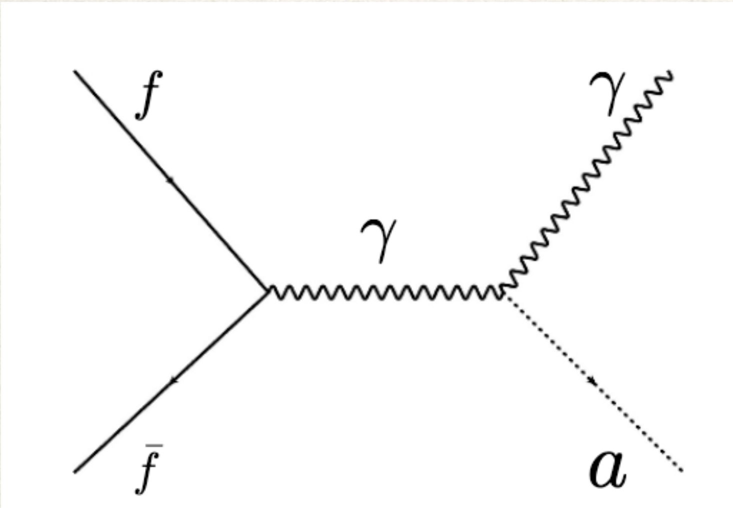


Assume coupling to photons
if ALP is collider-stable, this coupling would lead to **monophoton** (photon+MET)
if unstable, **tri-photon** or **diphoton** (boost)



ALPs at colliders

Mimasu, VS. JHEP (15)

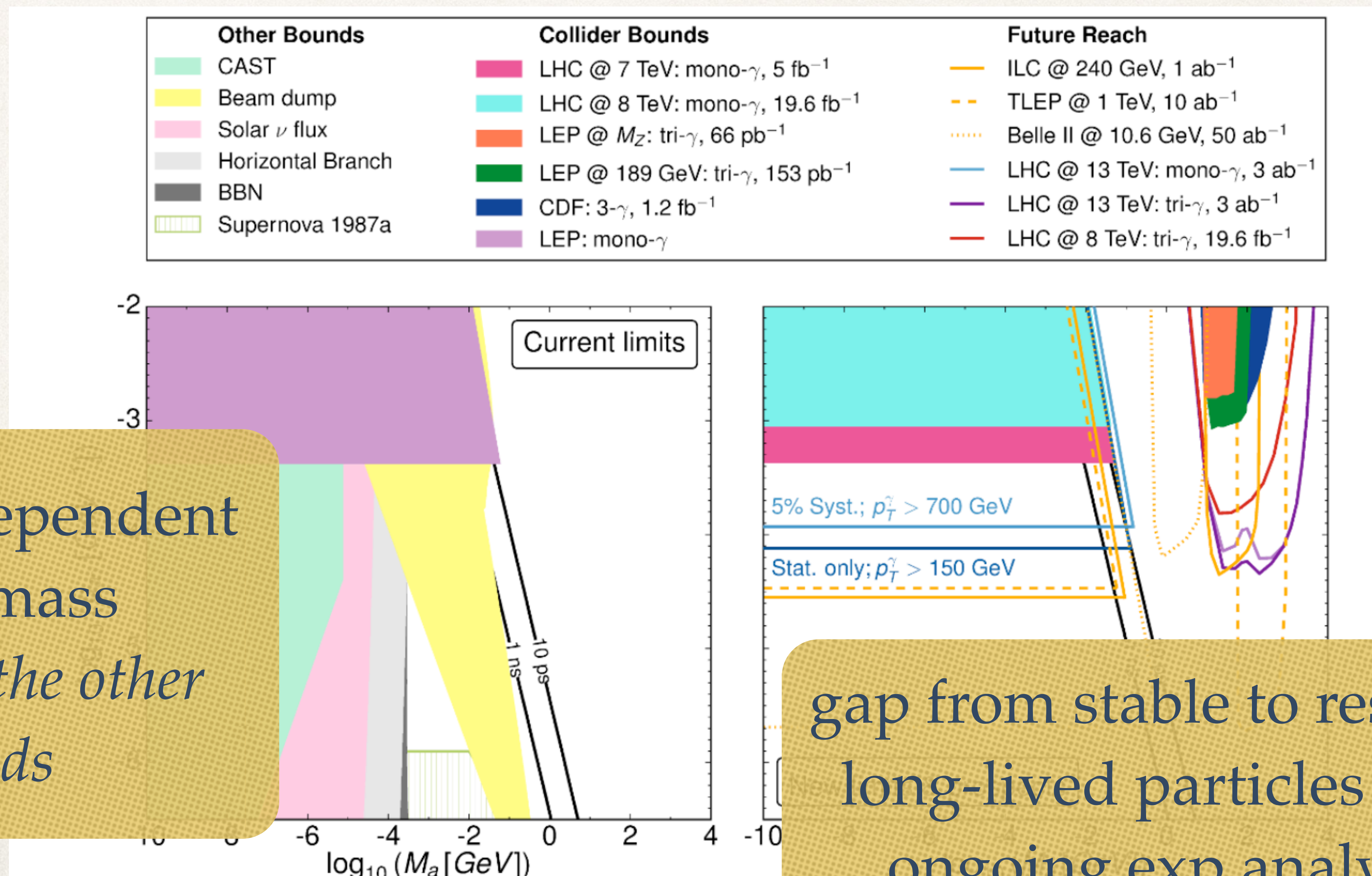


Assume coupling to photons

if ALP is collider-stable, this coupling would lead to

monophoton (photon+MET)

if it decays **tri-photon** or **diphoton** (boost)



mostly independent of the mass

crosses all the other bounds

gap from stable to resonant long-lived particles (LLP) ongoing exp analyses

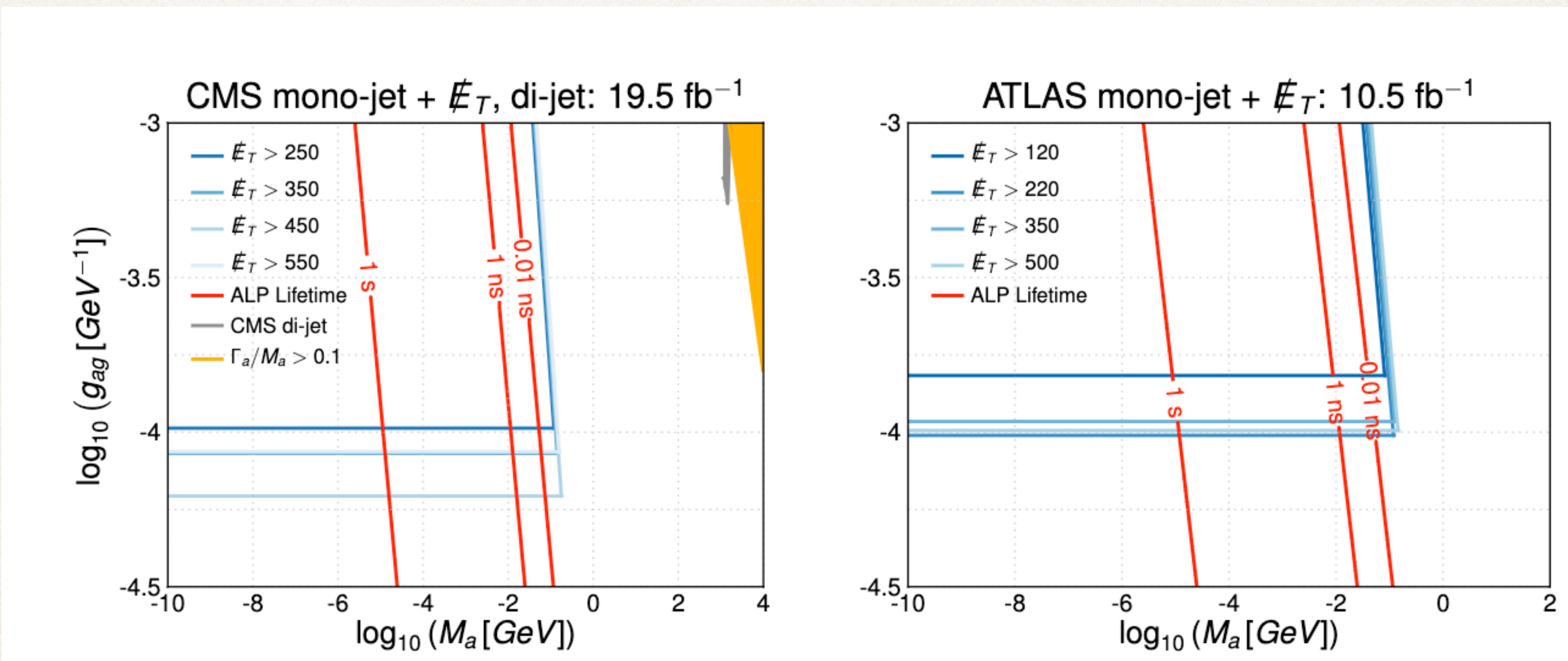
ALPs at colliders

Mimasu, VS. JHEP (15)

In axion models, coupling to gluons also generated

$$\mathcal{L} \supset \frac{c_{ag}}{f_a}\, a\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

mono-jet signature (jet+MET) or **dijets**



dijets= 3 jets, but two very collimated jets

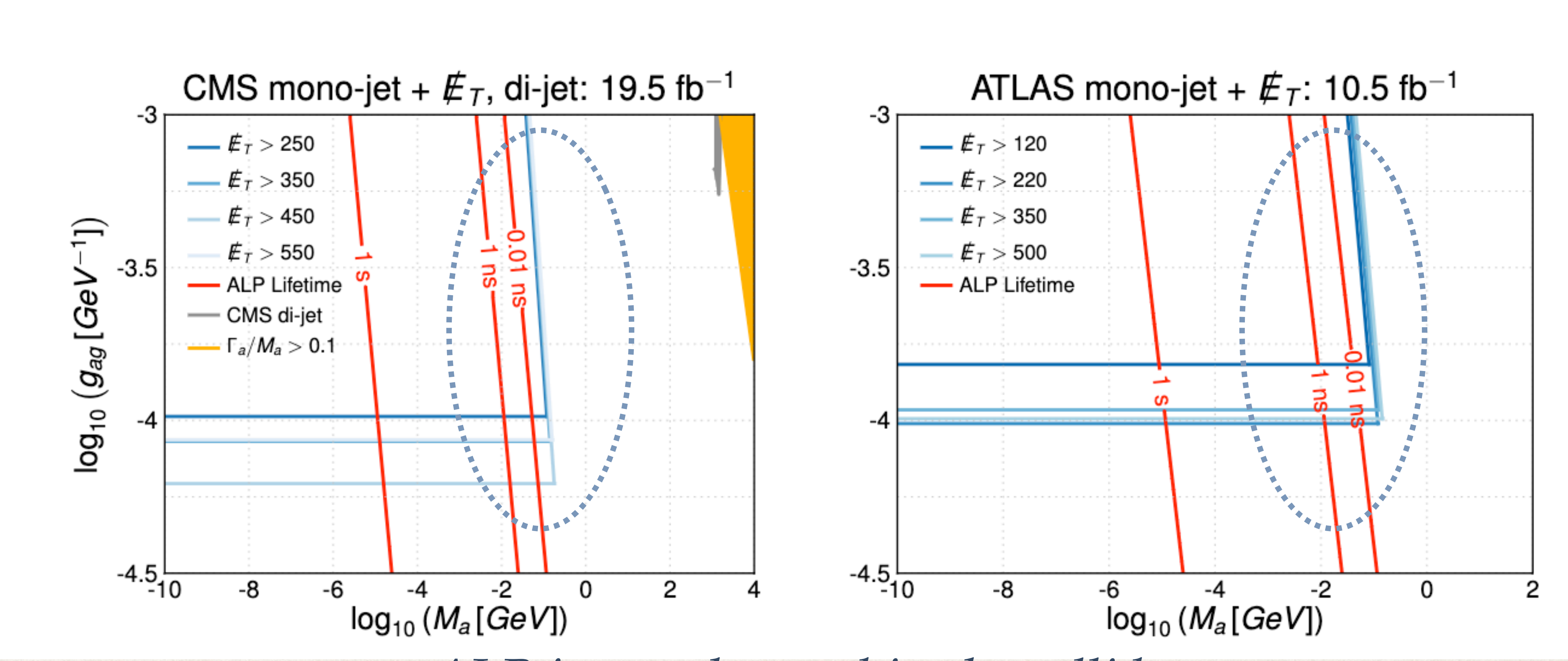
ALPs at colliders

Mimasu, VS. JHEP (15)

In axion models, coupling to gluons also generated

$$\mathcal{L} \supset \frac{c_{a\,g}}{f_a}\, a\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

mono-jet signature (jet+MET) or **dijets**



ALP is very boosted in the collider

range of collider stability depends on boost

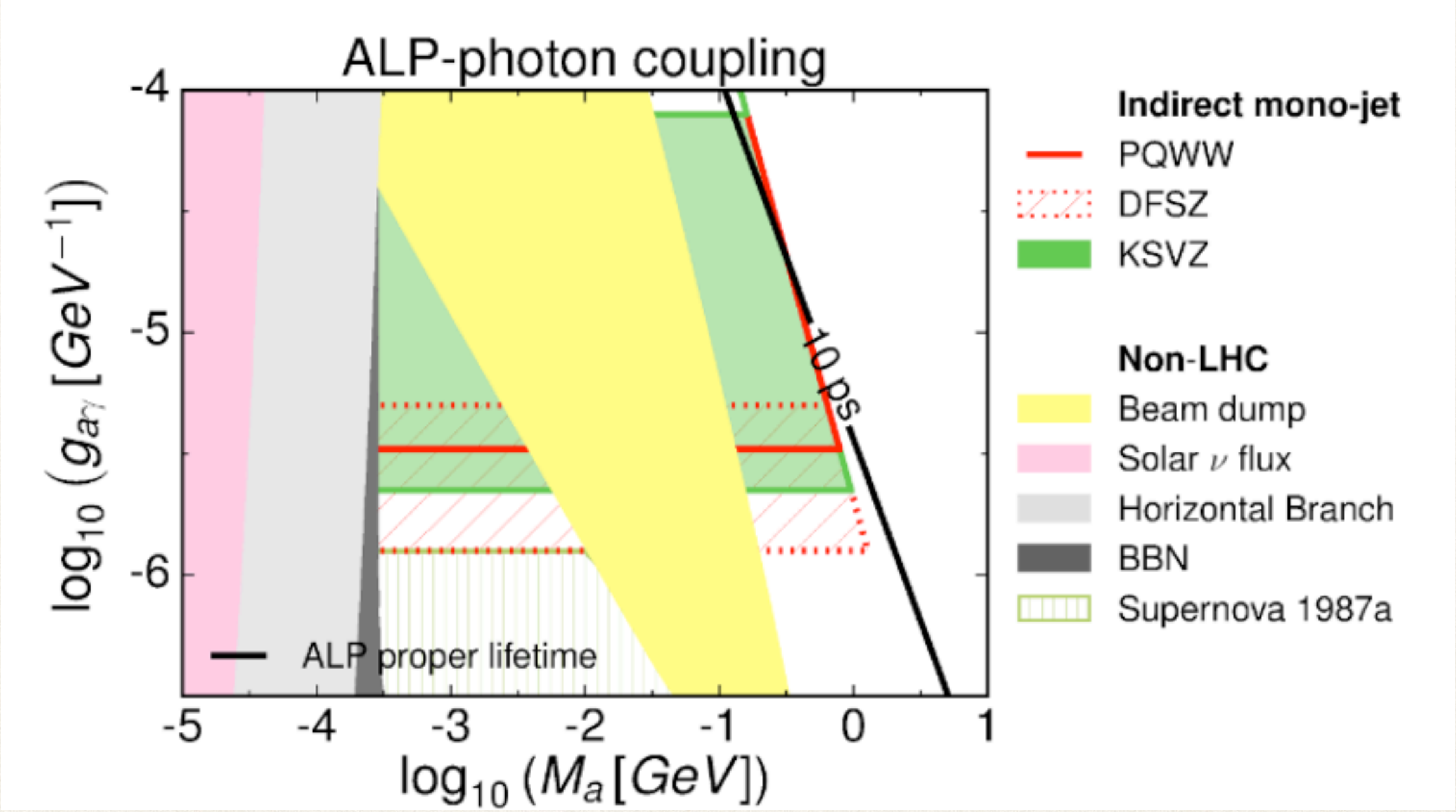
ALPs at colliders

Mimasu, VS. JHEP (15)

Coupling to gluons more constrained than to photons

In axion models, coupling to gluons also generated with a particular **relation** with the photon coupling

monophoton to monojet *enlarged sensitivity*

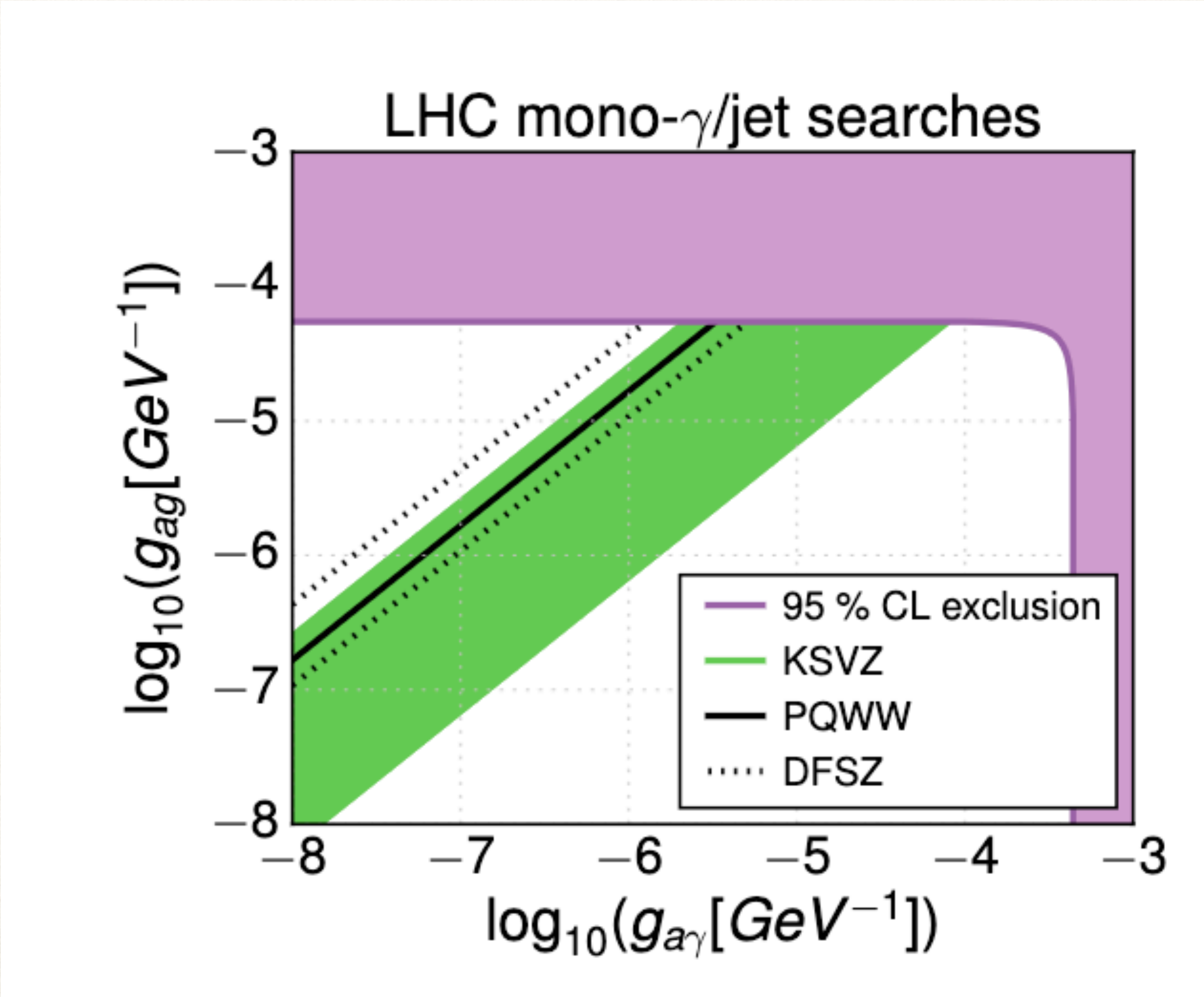


ALPs at colliders

Mimasu, VS. JHEP (15)

Coupling to gluons more constrained than to photons

In axion models, coupling to gluons also generated with a particular **relation** with the photon coupling



Coupling to EWSB sector

Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

the axion coupling **must** preserve the SM gauge structure
coupling to photons —> coupling to SU(3)XSU(2)XU(1)

$$\delta \mathscr{L}_a^{\text{bosonic}} = c_{\tilde{W}} \mathcal{A}_{\tilde{W}} + c_{\tilde{B}} \mathcal{A}_{\tilde{B}} + c_{\tilde{G}} \mathcal{A}_{\tilde{G}} + c_{a\Phi} \mathbf{O}_{a\Phi}$$

$$\mathcal{A}_{\tilde{B}} = -B_{\mu\nu} \tilde{B}^{\mu\nu} \frac{a}{f_a},$$

$$\mathcal{A}_{\tilde{W}} = -W^a_{\mu\nu} \tilde{W}^{a\mu\nu} \frac{a}{f_a},$$

$$\mathcal{A}_{\tilde{G}} = -G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \frac{a}{f_a},$$

coupling to gauge bosons

$$\mathbf{O}_{a\Phi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) \frac{\partial^\mu a}{f_a},$$

coupling to the Higgs

Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

Those couplings, after EWSB, induce coupling to mass eigenstates

$$\delta\mathcal{L}_{\rm eff} \supset -\frac{g_{agg}}{4} aG_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{g_{a\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{aZ\gamma}}{4} aF_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} aZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} aW_{\mu\nu}\tilde{W}^{\mu\nu},$$

$$g_{agg} = \frac{4}{f_a} c_{\tilde{G}}, \quad g_{a\gamma\gamma} = \frac{4}{f_a}(s_w^2 c_{\tilde{W}} + c_w^2 c_{\tilde{B}}), \quad g_{aWW} = \frac{4}{f_a} c_{\tilde{W}}, \quad g_{aZZ} = \frac{4}{f_a}(c_w^2 c_{\tilde{W}} + s_w^2 c_{\tilde{B}}),$$

$$g_{a\gamma Z} = \frac{8}{f_a} s_w c_w (c_{\tilde{W}} - c_{\tilde{B}}),$$

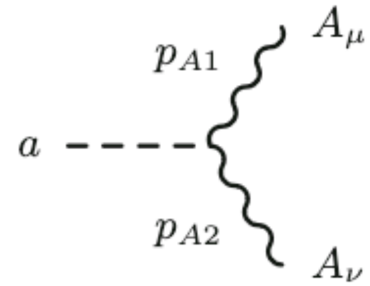
Coupling to Higgs can be re-casted as
mass & flavour dependent **coupling to fermions**

$$i\frac{a}{f_a}[\bar{Q}Y_u\tilde{\Phi}u_R - \bar{Q}Y_d\Phi d_R - \bar{L}Y_\ell\Phi\ell_R] + \text{H.c.},$$

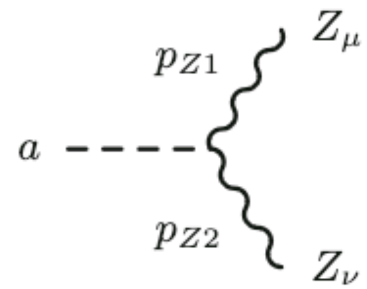
Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

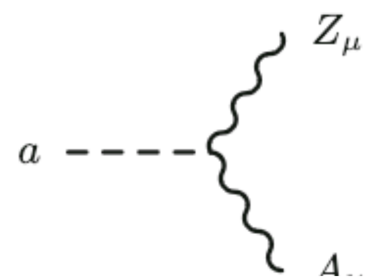
Linear ALP



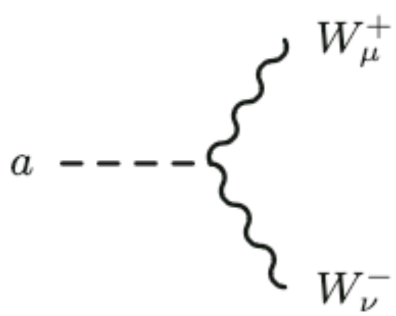
$$-\frac{4i}{f_a} p_{A1\alpha} p_{A2\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_\theta^2 c_{\tilde{B}} + s_\theta^2 c_{\tilde{W}}\right)$$



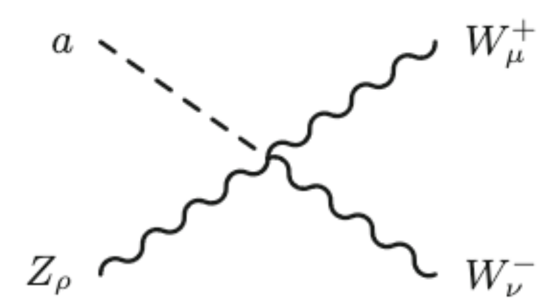
$$-\frac{4i}{f_a} p_{Z1\alpha} p_{Z2\beta} \varepsilon^{\mu\nu\alpha\beta} \left(s_\theta^2 c_{\tilde{B}} + c_\theta^2 c_{\tilde{W}}\right)$$



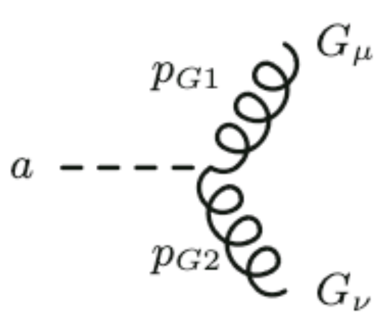
$$\frac{2is_{2\theta}}{f_a} p_{Z\alpha} p_{A\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_{\tilde{B}} - c_{\tilde{W}}\right)$$



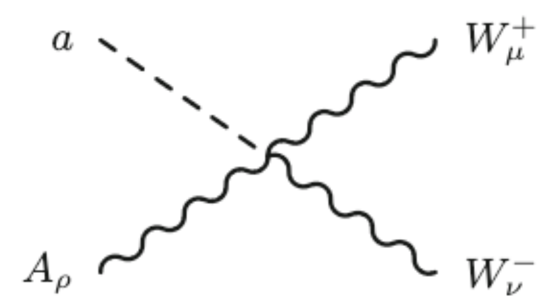
$$-\frac{4i}{f_a} c_{\tilde{W}} p_{+\alpha} p_{-\beta} \varepsilon^{\mu\nu\alpha\beta}$$



$$-\frac{4igc_\theta}{f_a} c_{\tilde{W}} \varepsilon^{\mu\nu\rho\alpha} p_{a\alpha}$$



$$-\frac{4i}{f_a} c_{\tilde{G}} \, p_{G1\alpha} p_{G2\beta} \, \varepsilon^{\mu\nu\alpha\beta}$$

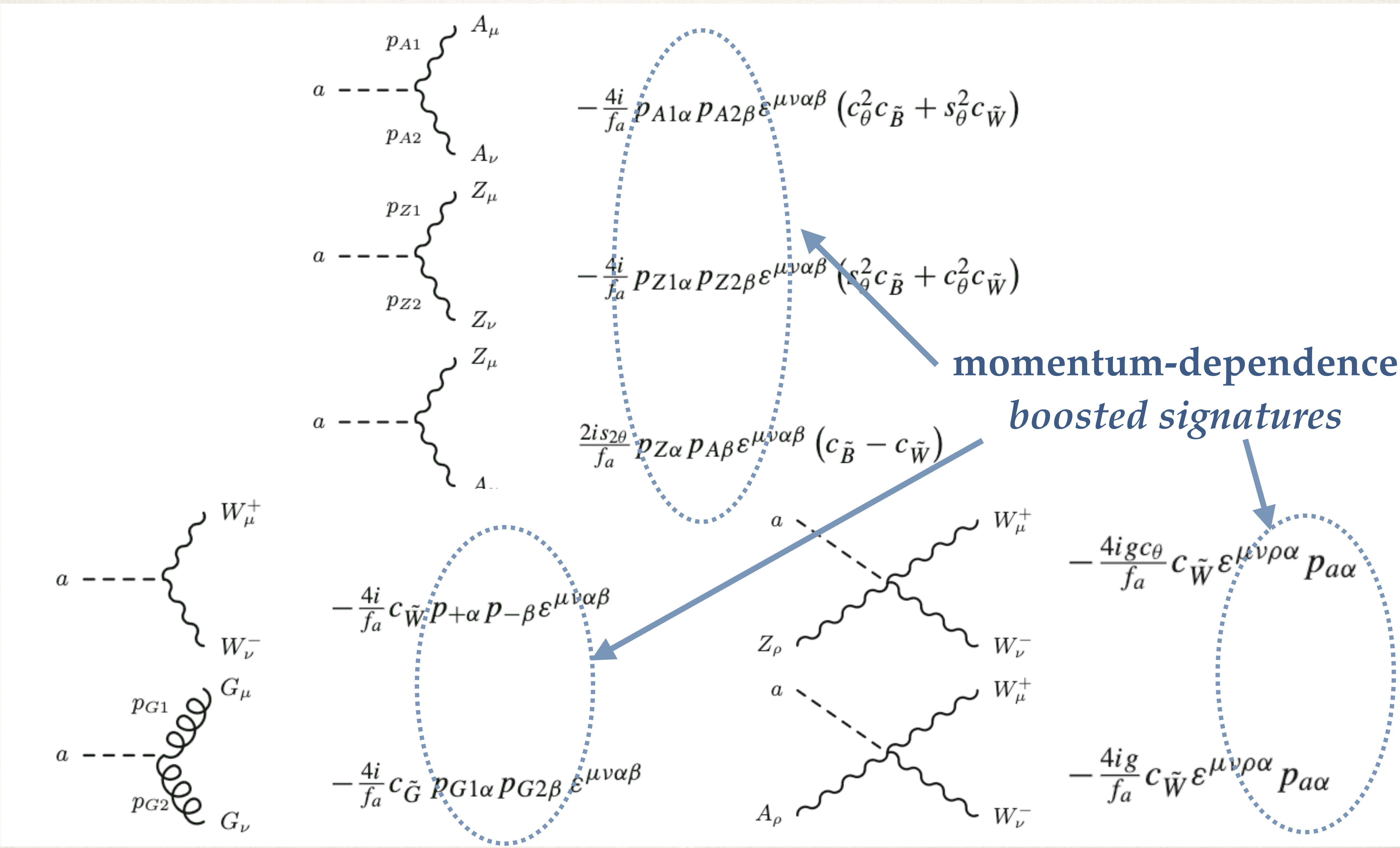


$$-\frac{4ig}{f_a} c_{\tilde{W}} \varepsilon^{\mu\nu\rho\alpha} p_{a\alpha}$$

Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

Linear ALP

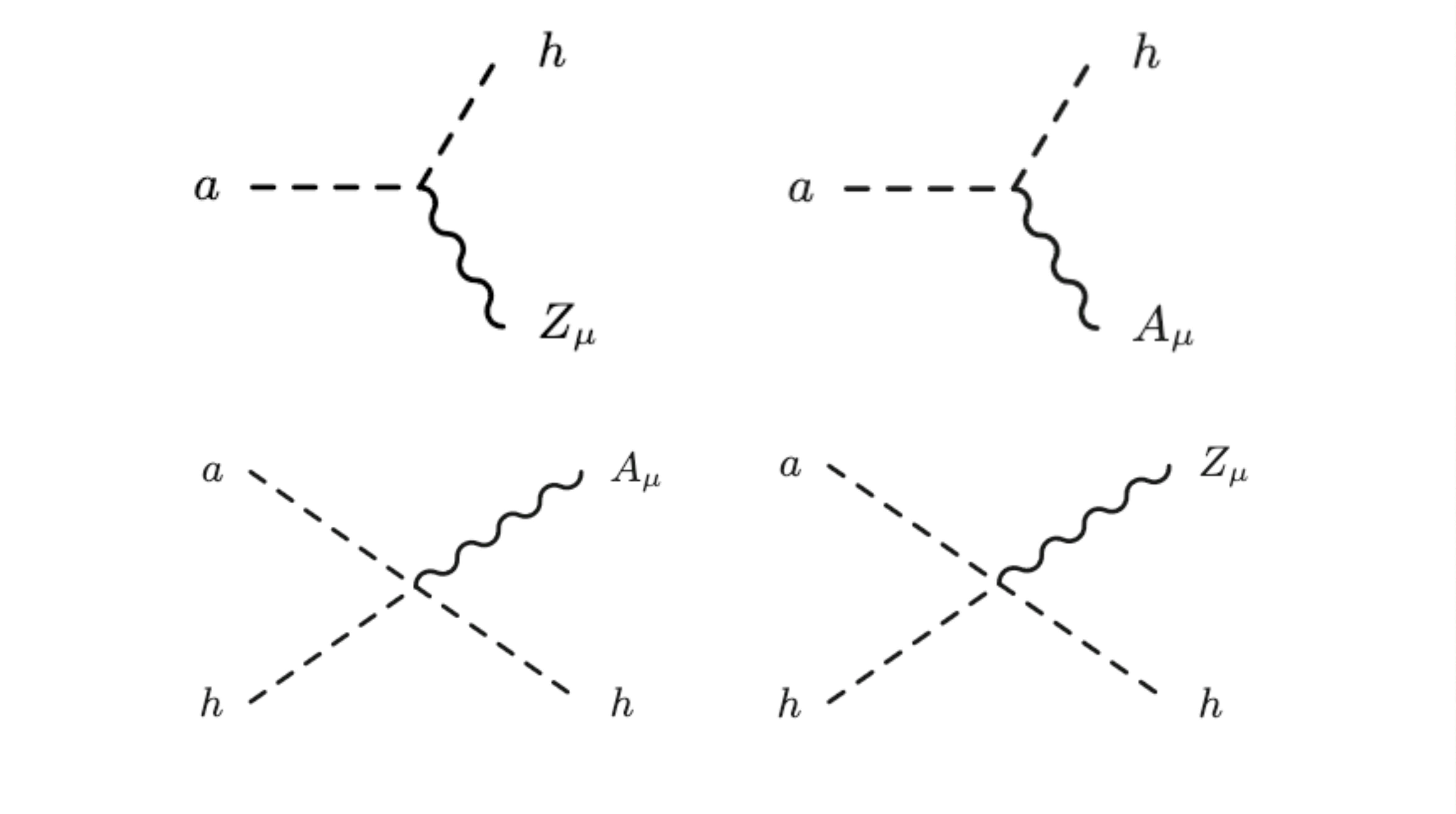


Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

If EWSB is non-linearly realized, **Chiral ALP**

many more terms, **new couplings**
for example

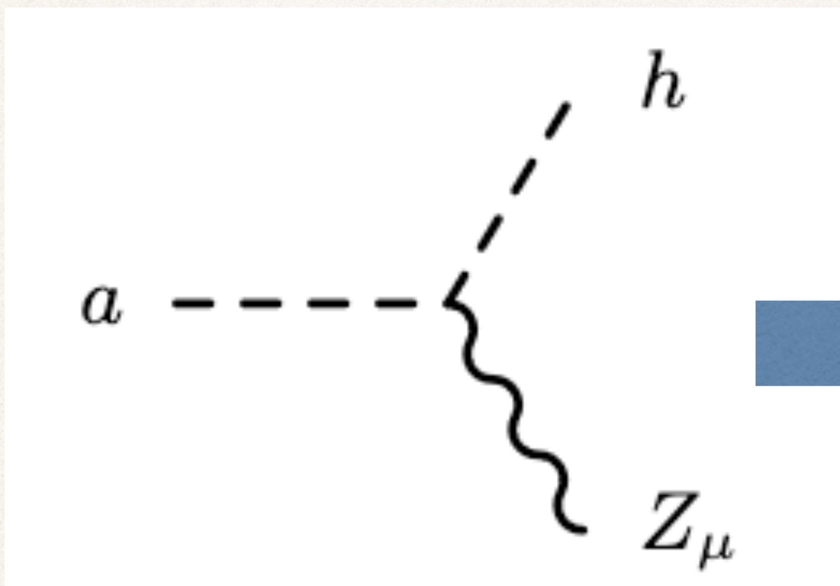


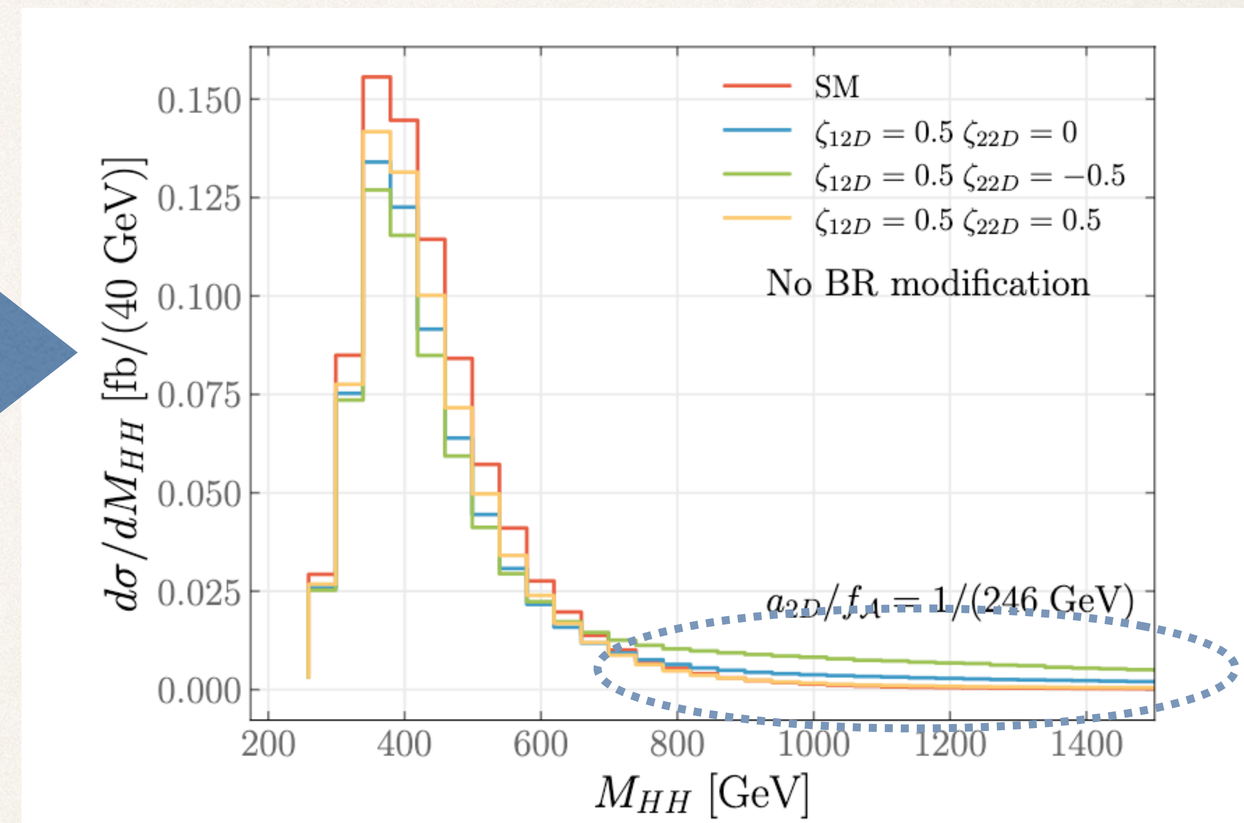
Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

If EWSB is non-linearly realized, **Chiral ALP**

many more terms, **new couplings**
for example





recent study of di-Higgs

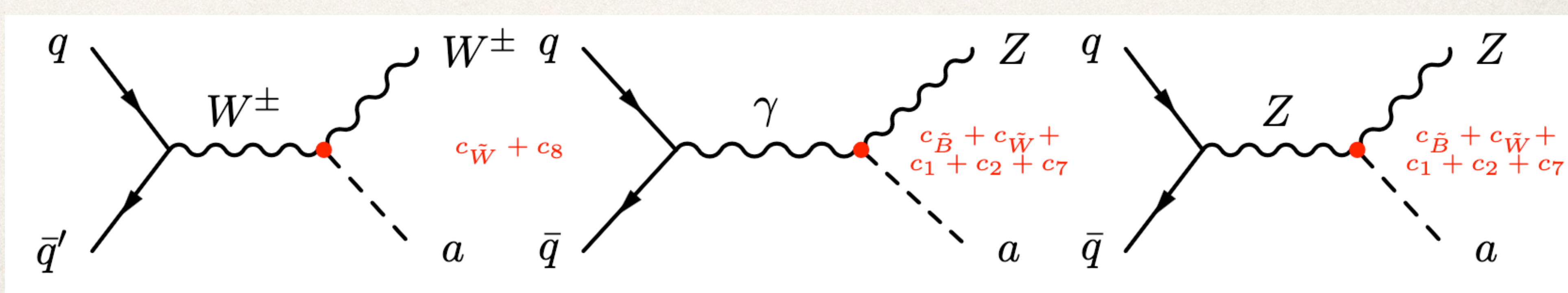
Anisha, Das Kakshi, Englert, Stilyanou.
2306.11808

Bosonic ALP

Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)

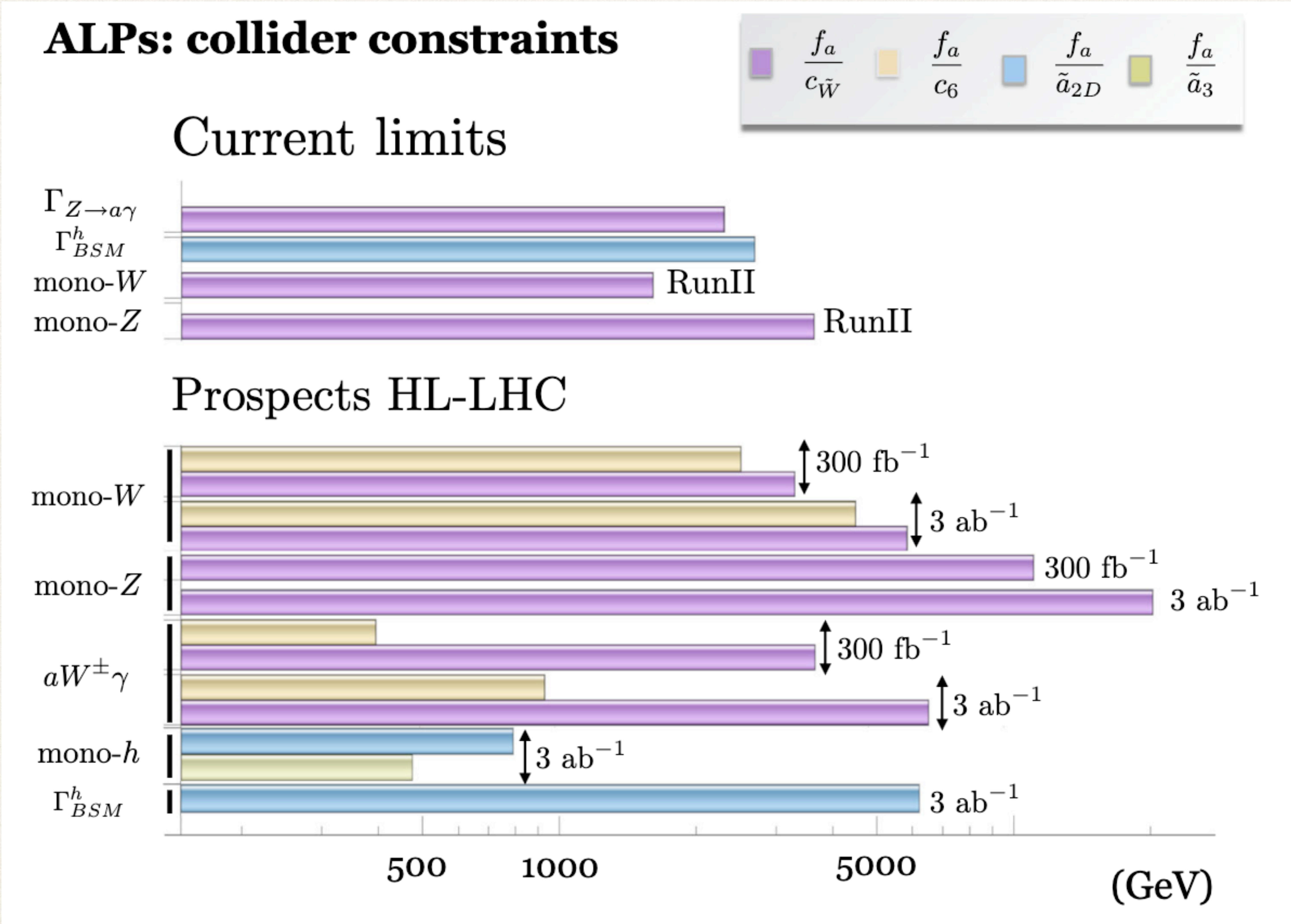
Observables/processes		Parameters contributing														
		Linear			Non-linear											
Astrophysical obs.	$g_{a\gamma\gamma}$	$\mathbf{c_{\tilde{W}}}$	$\mathbf{c_{\tilde{B}}}$		$\mathbf{c_{\tilde{W}}}$	$\mathbf{c_{\tilde{B}}}$										
Rare meson decays		$\mathbf{c_{\tilde{W}}}$		$\mathbf{c_{a\Phi}}$	$\mathbf{c_{\tilde{W}}}$		$\mathbf{c_{2D}}$		c_2		c_6		c_8			c_{17}
New constraints																
LEP data																
BSM Z width	$\Gamma(Z \to a\gamma)$	$\mathbf{c_{\tilde{W}}}$	$\mathbf{c_{\tilde{B}}}$		$\mathbf{c}_{\tilde{W}}$	$\mathbf{c_{\tilde{B}}}$		c_1	c_2			c_7				
LHC processes																
Non-standard h decays	$\Gamma(h \to aZ)$						$\mathbf{\tilde{a}_{2D}}$			$\tilde{a}_3$				$\tilde{a}_{10}$	$\tilde{a}_{11-14}$	$\tilde{a}_{17}$
Mono-Z prod.	$pp \to a\,Z$	$\mathbf{c_{\tilde{W}}}$	$\mathbf{c_{\tilde{B}}}$	$c_{a\Phi}$	$\mathbf{c_{\tilde{W}}}$	$\mathbf{c}_{\tilde{B}}$	c_{2D}	c_1	c_2	c_3		c_7		c_{10}	c_{11-14}	c_{17}
Mono-W prod.	$pp \to a\,W^{\pm}$	$\mathbf{c_{\tilde{W}}}$	$c_{\tilde{B}}$	$c_{a\Phi}$	$\mathbf{c_{\tilde{W}}}$	$c_{\tilde{B}}$	c_{2D}		c_2		$\mathbf{c_6}$		c_8	c_{10}		
Prospects																
Associated prod.	$pp \to aW^{\pm}\gamma$	$\mathbf{c_{\tilde{W}}}$	$c_{\tilde{B}}$	$c_{a\Phi}$	$\mathbf{c_{\tilde{W}}}$	$c_{\tilde{B}}$	c_{2D}	c_1	c_2		$\mathbf{c_6}$	c_7	c_8			
VBF prod.	$pp \to ajj(\gamma)$	$c_{\tilde{W}}$	$c_{\tilde{B}}$	$c_{a\Phi}$	$c_{\tilde{W}}$	$c_{\tilde{B}}$	c_{2D}	c_1	c_2		c_6	c_7	c_8			
Mono-h prod.	$pp \to h\,a$						$\mathbf{\tilde{a}_{2D}}$			$\mathbf{\tilde{a}_3}$				$\mathbf{\tilde{a}_{10}}$	$\tilde{a}_{11-14}$	$\tilde{a}_{17}$
$at\bar{t}$ prod.	$pp \to at\bar{t}$			$\mathbf{c_{a\Phi}}$			$\mathbf{c_{2D}}$									

e.g. mono-W and mono-Z



Bosonic ALP

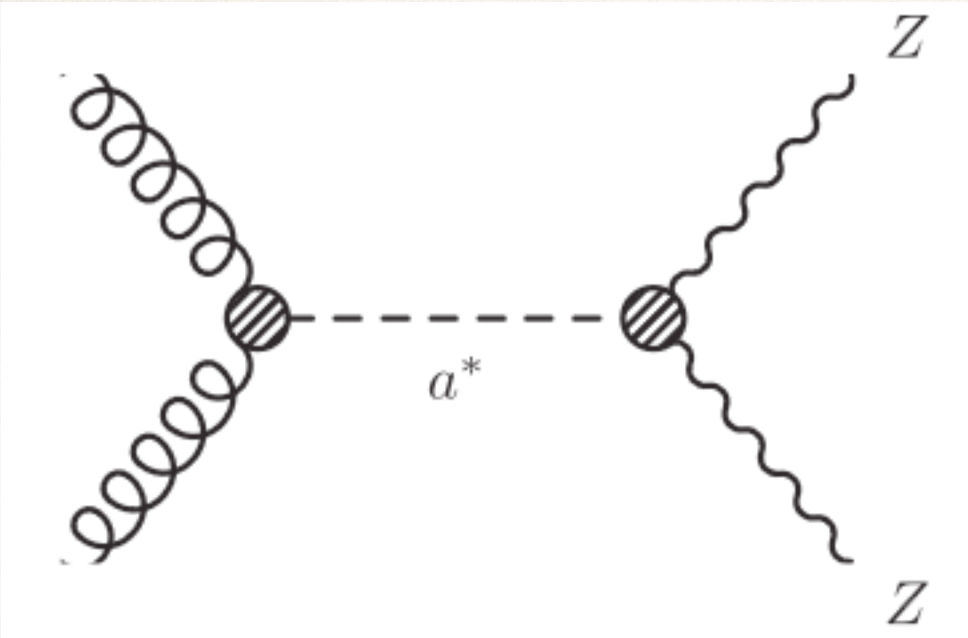
Brivio, Gavela, Merlo, Mimasu, No, Rey, VS. EPJC (17)



Exploiting the boosted kinematics
Non-resonant searches

Non-resonant searches

Gavela, No, VS, Troconiz. Phys Rev Lett (20)



Derivative couplings
—> Momentum dependent
—> off-shell production is not suppressed

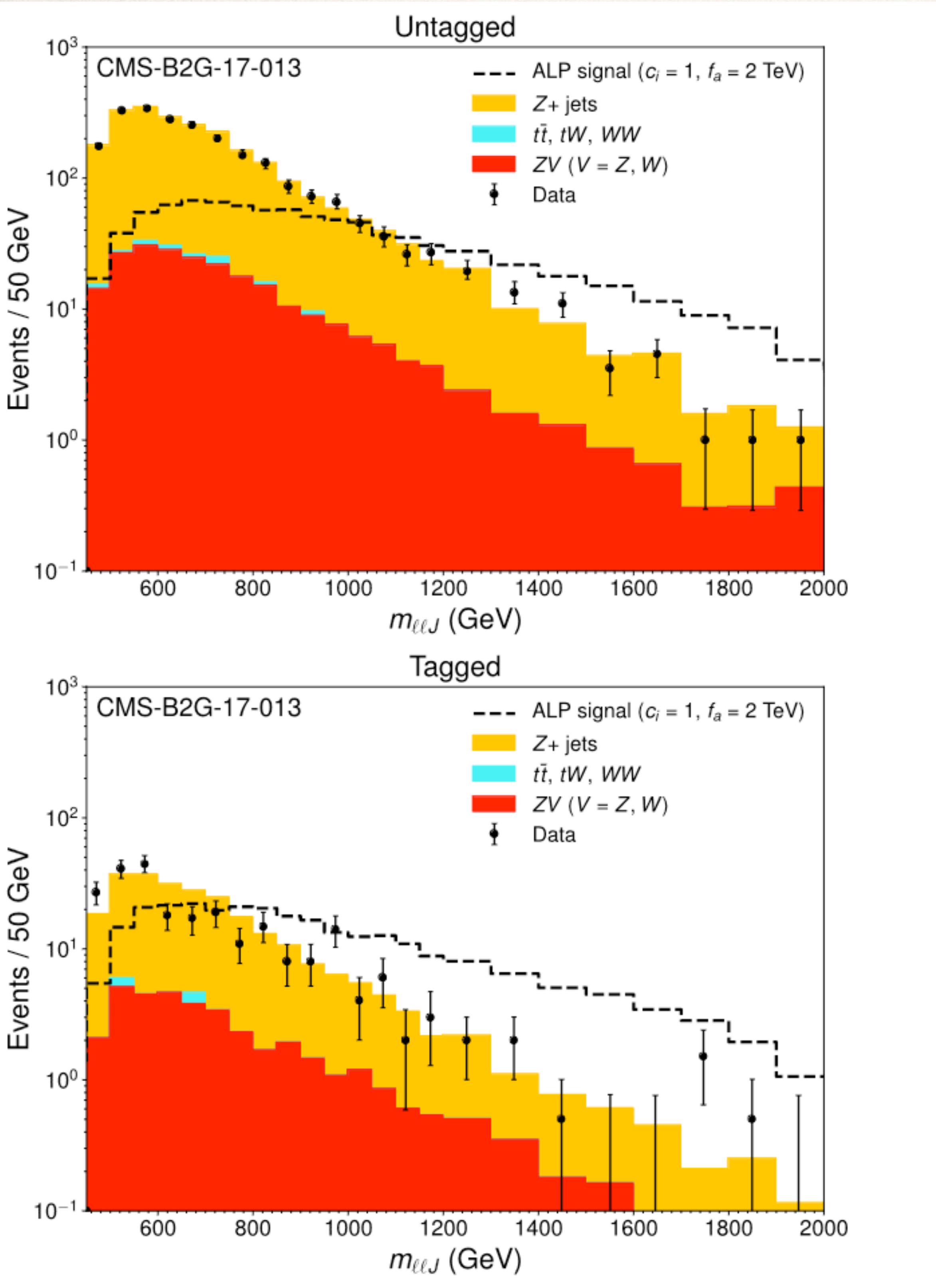
This is no longer (production X BR) but

$$\sigma_{V_1V_2} \propto g^2_{agg} g^2_{aV_1V_2} \hat{s} \sim \frac{\hat{s}}{f_a^4},$$

where $\sqrt{\hat{s}} = m_{V_1V_2}$

Non-resonant searches

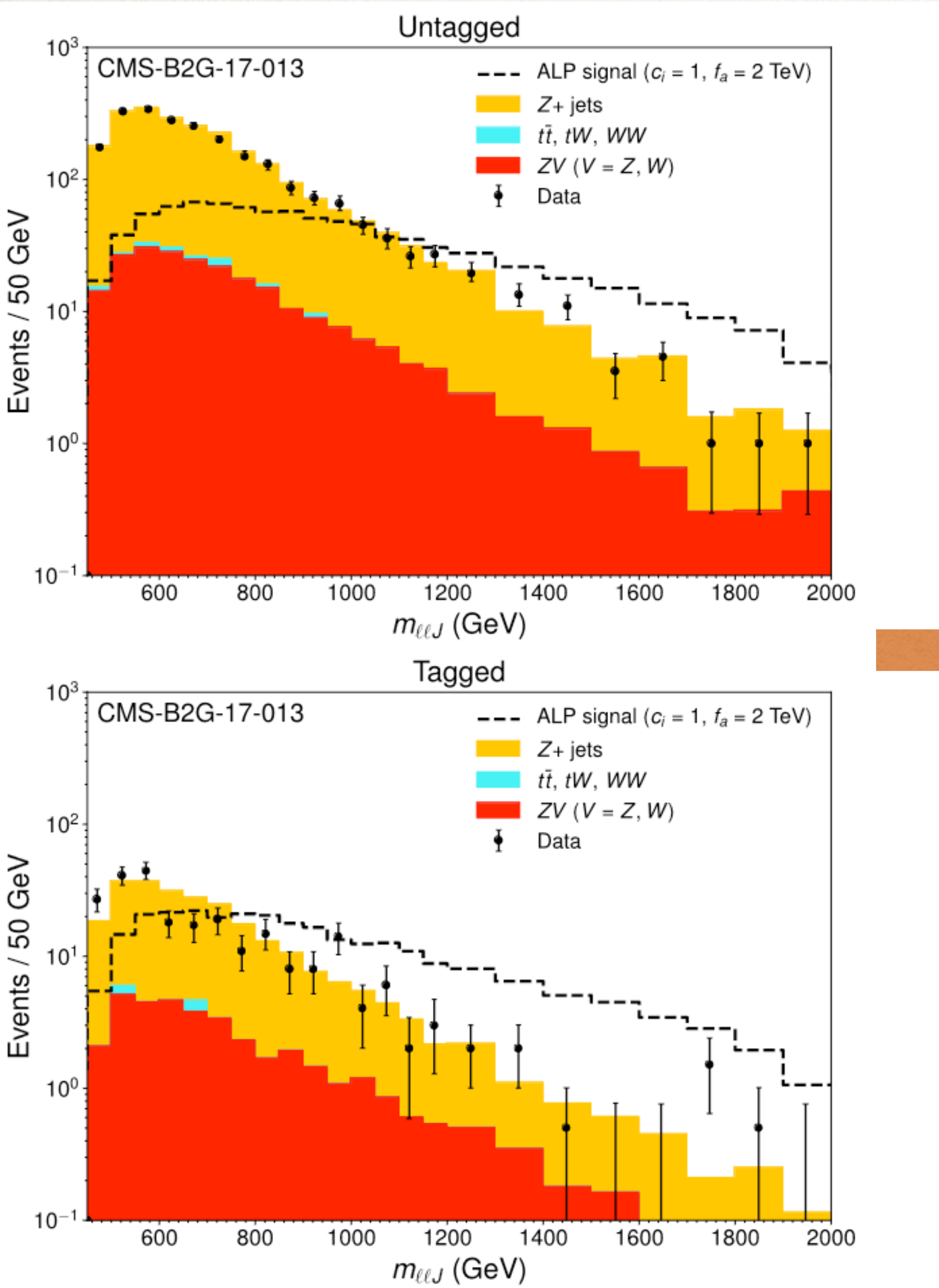
Gavela, No, VS, Troconiz. Phys Rev Lett (20)



Similarly to SMEFT, ALP off-shell production leads to kinematic growth

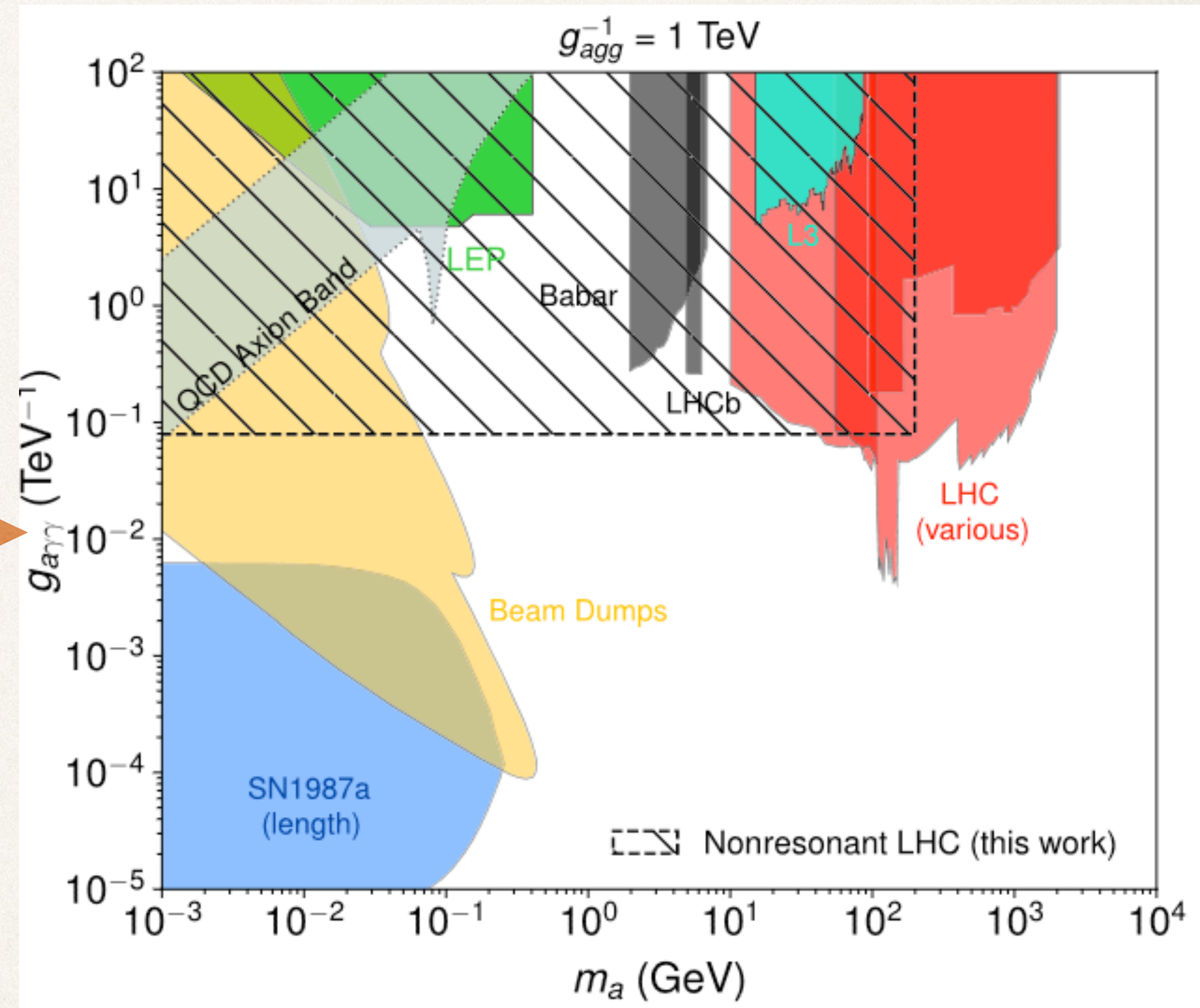
Non-resonant searches

Gavela, No, VS, Troconiz. Phys Rev Lett (20)



Similarly to SMEFT, ALP off-shell production leads to kinematic growth

e.g.



photon coupling vs mass

limits independent of mass up to resonant ZZ

Coupling to tops

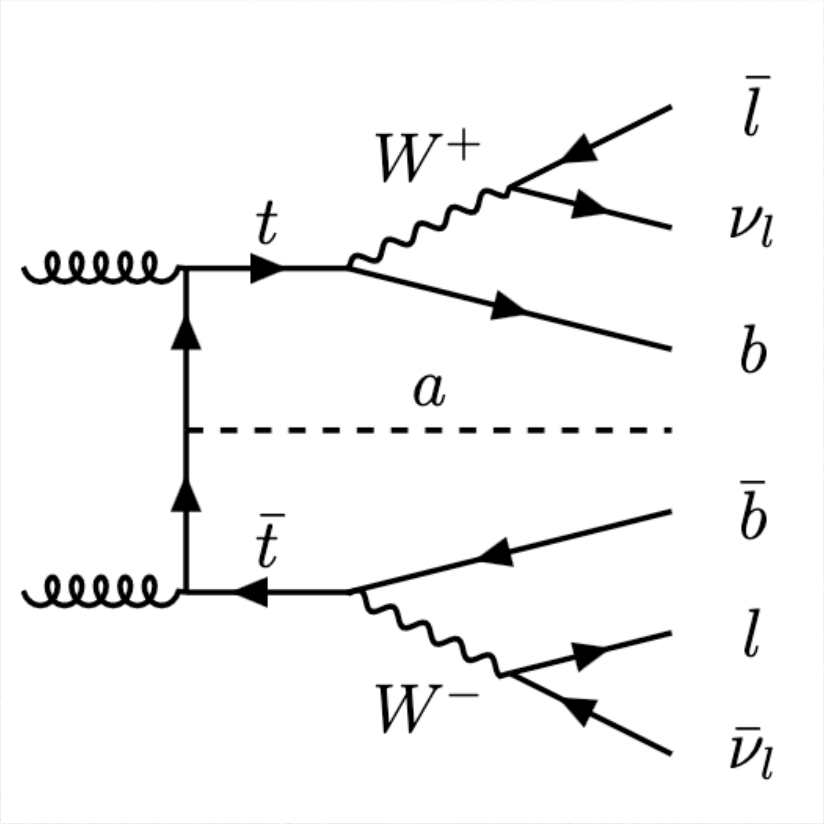
Axion-top coupling

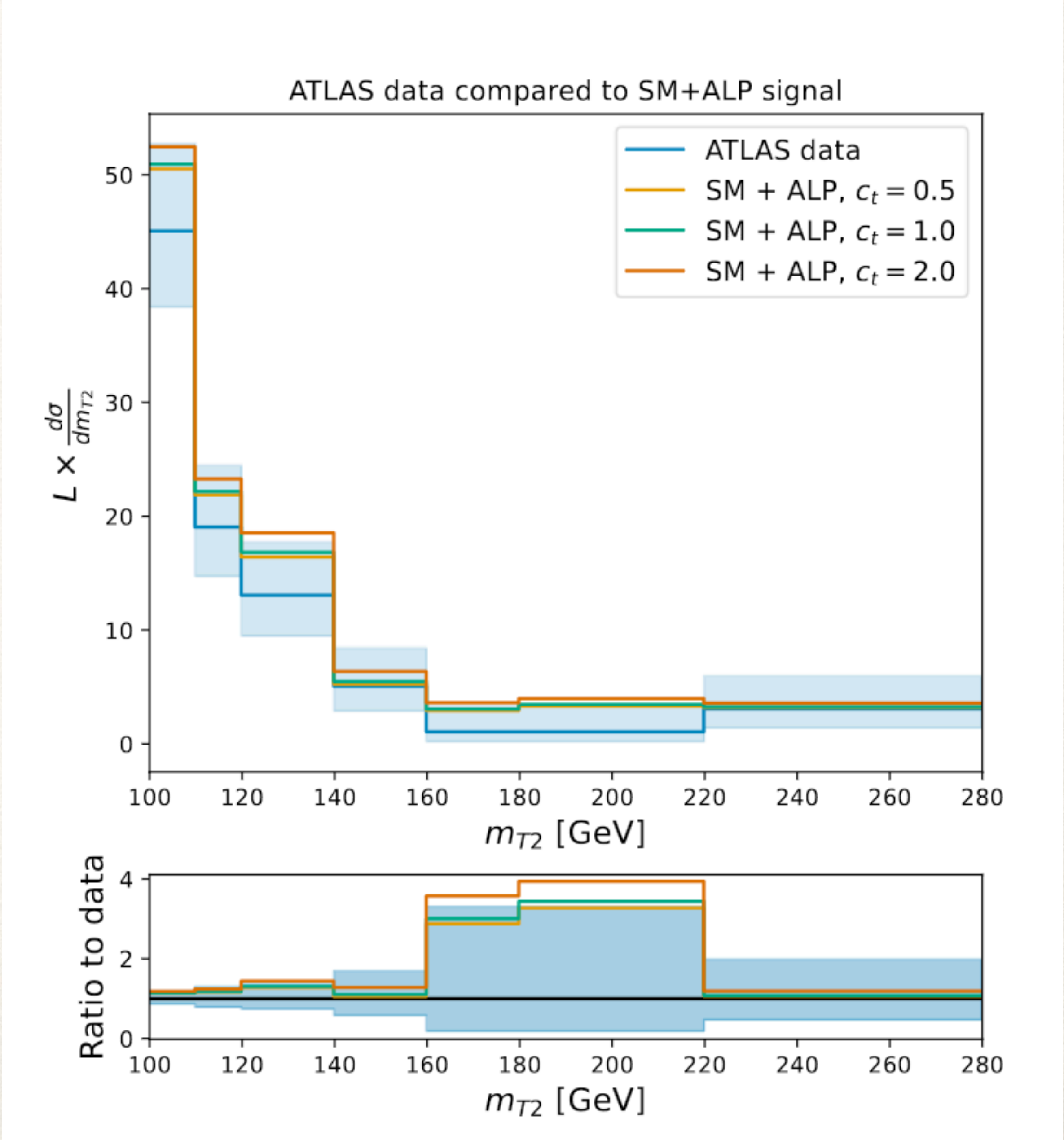
Esser, Madigan, VS, Ubiali. JHEP (23)

E.g.

$$\mathcal{L} = c_t \frac{\partial_\mu a}{2 f_a} (\bar{t}\gamma^\mu \gamma^5 t) \xrightarrow{\text{EOMs}} \mathcal{L} = -i\, c_t \frac{m_t a}{2 f_a} (\bar{t}\gamma^5 t)$$

We can directly access ttbar+ALP





Axion-top coupling

Esser, Madigan, VS, Ubiali. JHEP (23)

Axion-top coupling —> loop-induced coupling to other particles

Bonilla, Brivio, Gavela, VS. JHEP (22)

$$\hat{g}^{\text{eff}}_{a\gamma\gamma} = \hat{g}_{a\gamma\gamma} + \frac{2\alpha_{em}}{\pi s_w^2}\hat{g}_{aWW}B_2\left(\frac{4M_W^2}{p^2}\right) - \frac{4}{f_a}\sum_{\text{f}} c_{\text{f}} Q_{\text{f}}^2 N_C B_1\left(\frac{4m_{\text{f}}^2}{p^2}\right)$$

effective coupling to photons

from axion-top couplings

Regime	Expression
high-pT	$c^{\text{eff}}_{a\gamma\gamma} = -\frac{\alpha_{\text{em}}}{3\pi}c_{\text{t}}$
high-pT	$c^{\text{eff}}_{a\gamma Z} = \frac{2\alpha_{\text{em}}s_w}{3\pi c_w}c_{\text{t}}$
high-pT	$c^{\text{eff}}_{aZZ} = -\frac{\alpha_{\text{em}}s_w^2}{3\pi c_w^2}c_{\text{t}}$
high-pT	$c^{\text{eff}}_{aW^+W^-} = 0$
high-pT	$c^{\text{eff}}_{agg} = -\frac{\alpha_s}{8\pi}c_{\text{t}}$

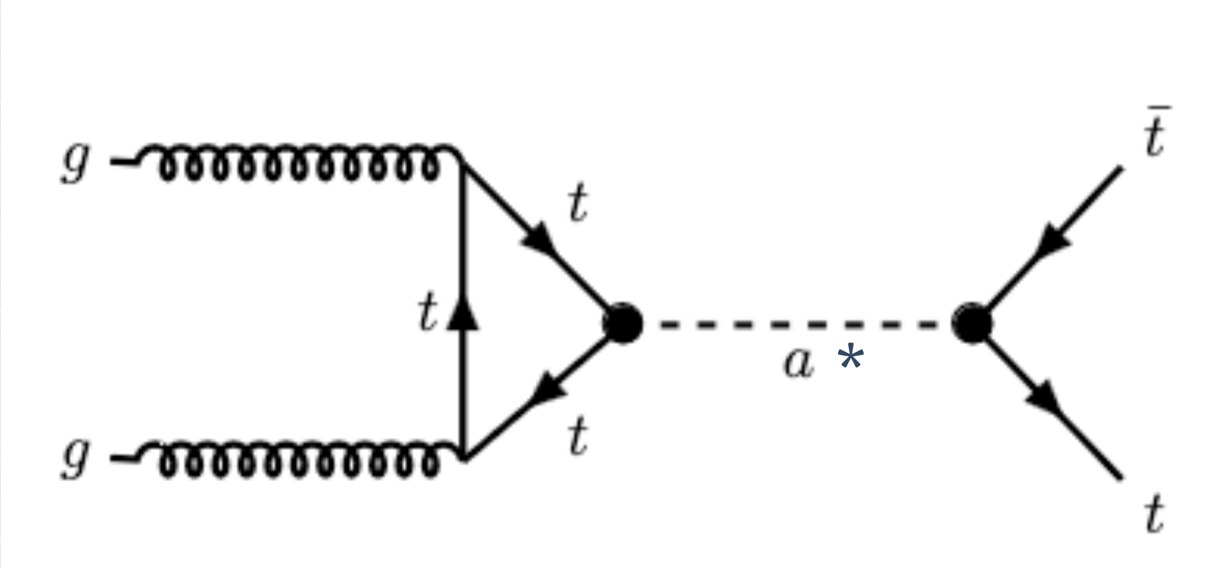
not generic
just a choice (R-handed)

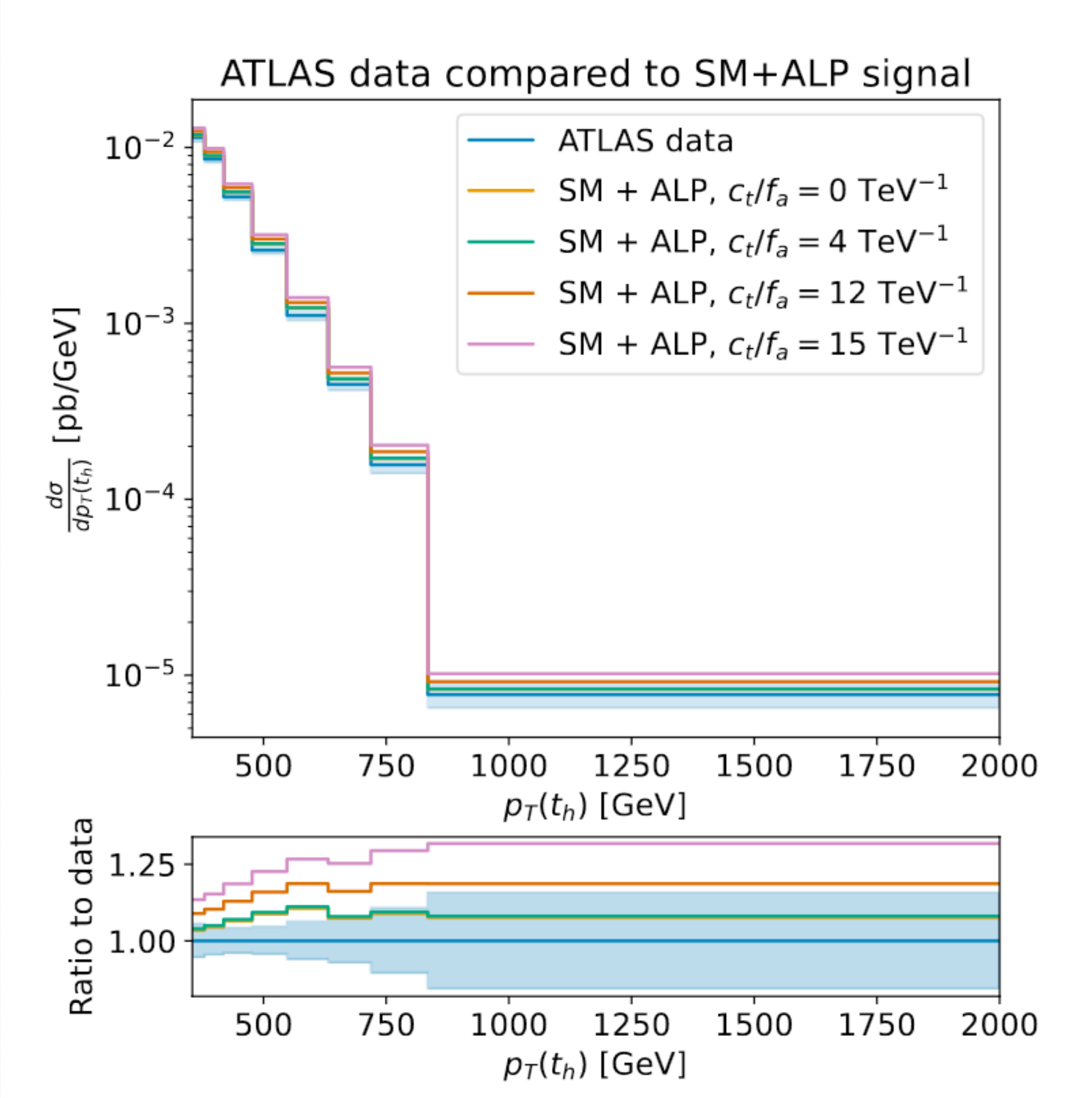
Axion-top coupling

Esser, Madigan, VS, Ubiali. JHEP (23)

Top coupling—> loop gluon coupling
—> production increases a lot, could overcome loop suppression

- relevant off-shell/non-resonant production

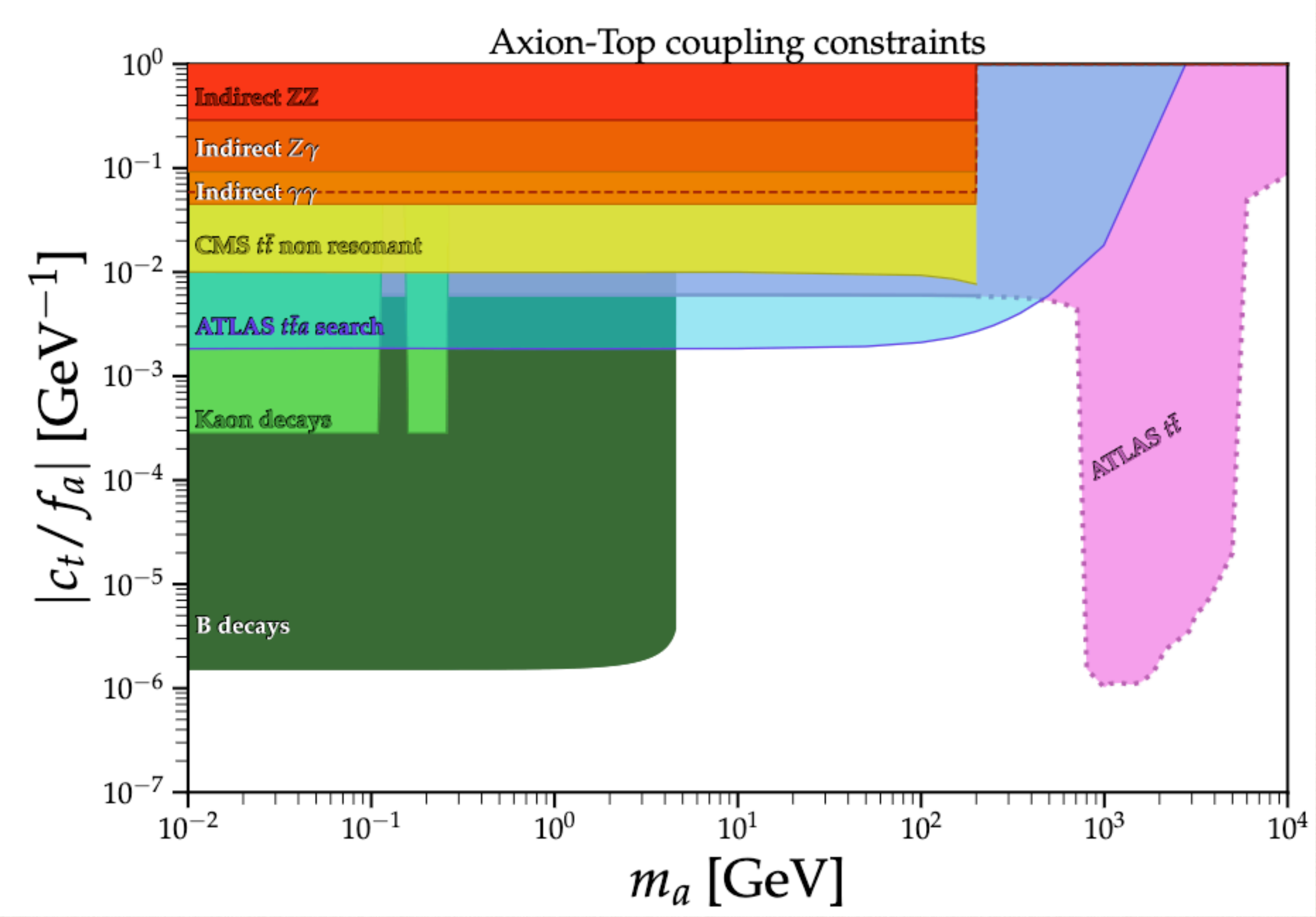




SM top measurements can be used to constrain the axion-top

Axion-top coupling

Esser, Madigan, VS, Ubiali. JHEP (23)

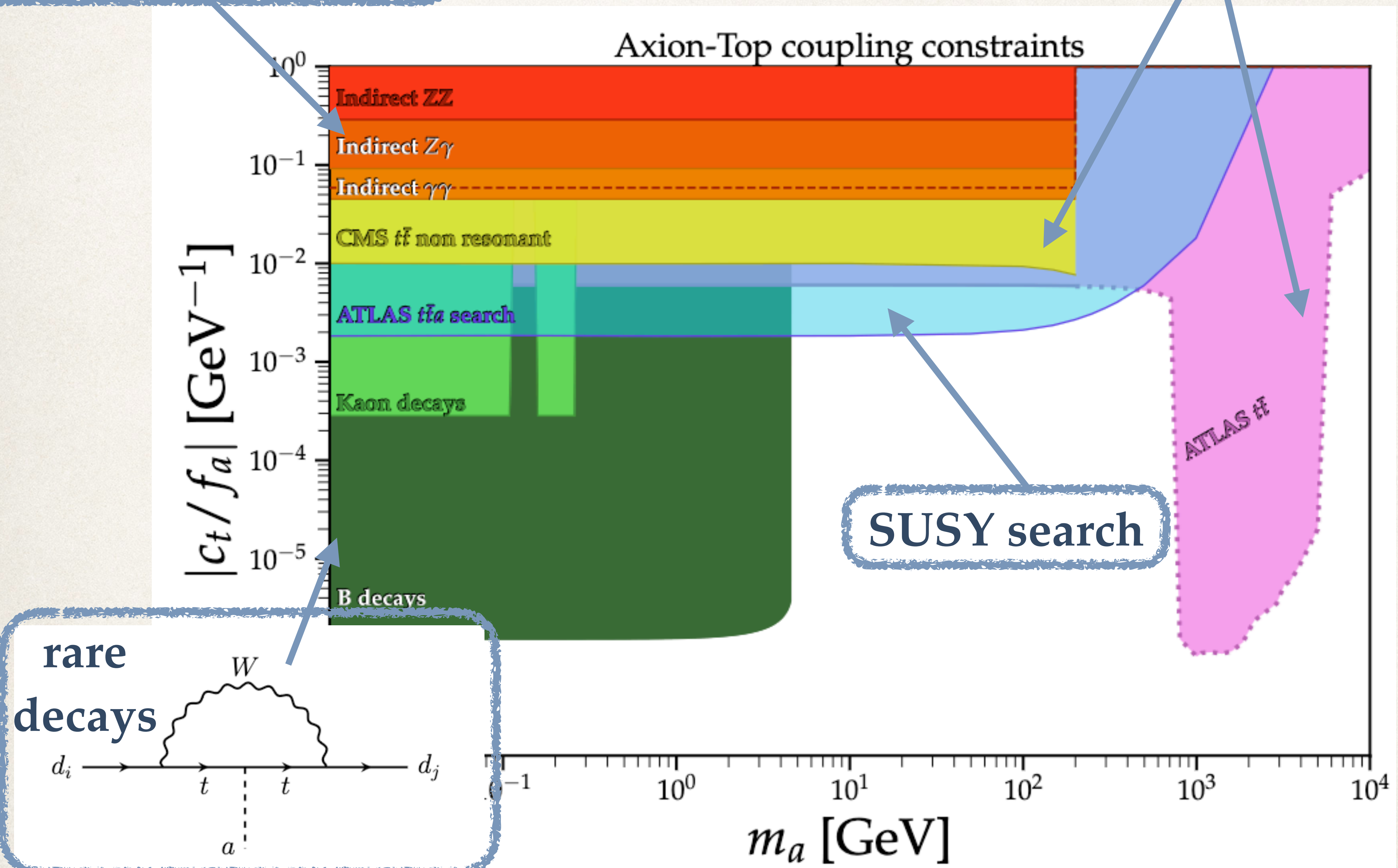


Axion-top coupling

Esser, Madigan, VS, Ubiali. JHEP (23)

indirect= recast from previous results

SM top measurements



SUSY search

rare decays

see also Chala, Guedes, Ramos, Santiago. EPJC(21)

No free lunch: Validity

The issue of validity

ALPs couple with a 1/(mass scale), is an EFT

EFTs are expansions in (E/f)

need to make sure we apply this description where it belongs

E<<f

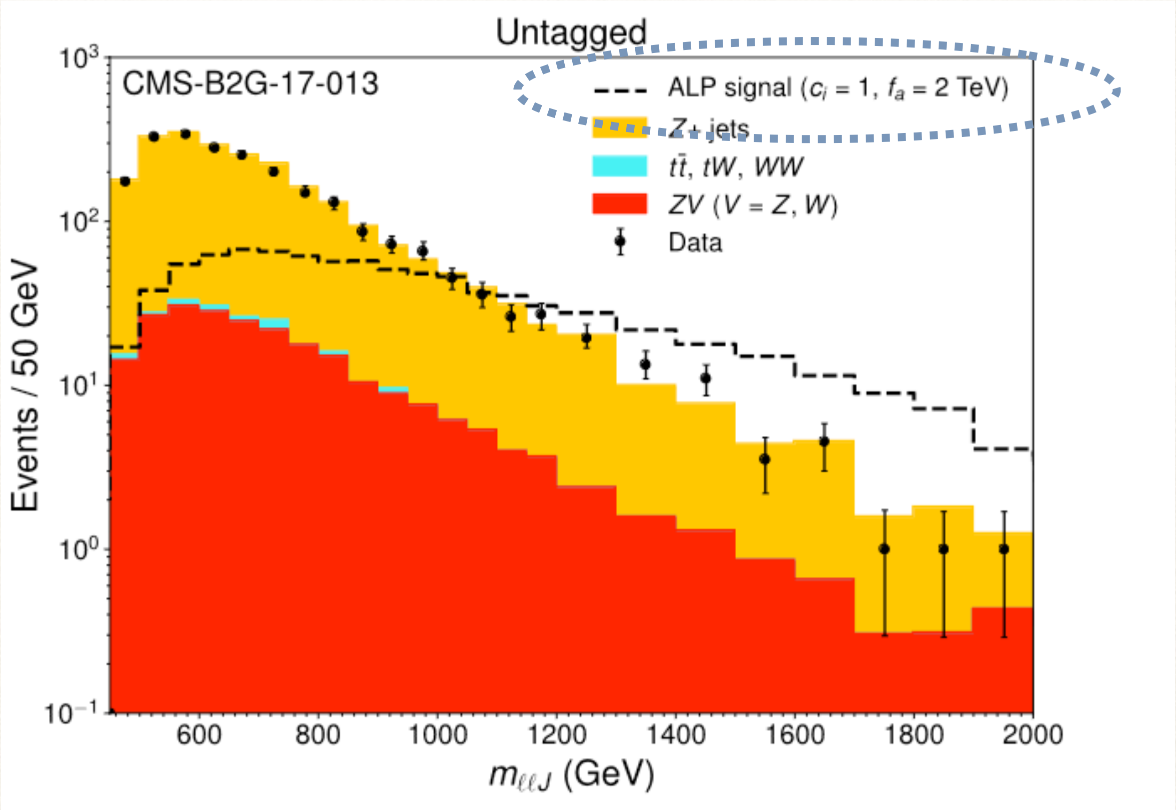
The issue of validity

ALPs couple with a 1/(mass scale), is an EFT
EFTs are expansions in (E/f)
need to make sure we apply this description where it belongs
E<<f

At hadron colliders, we have
a large kinematic range

e.g. ZZ production at the LHC

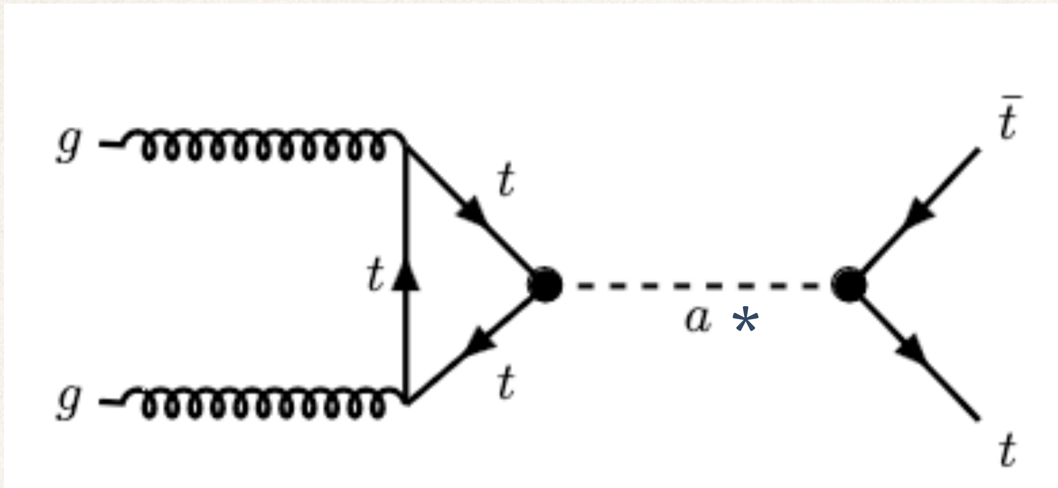
m(ZZ) =energy of the event

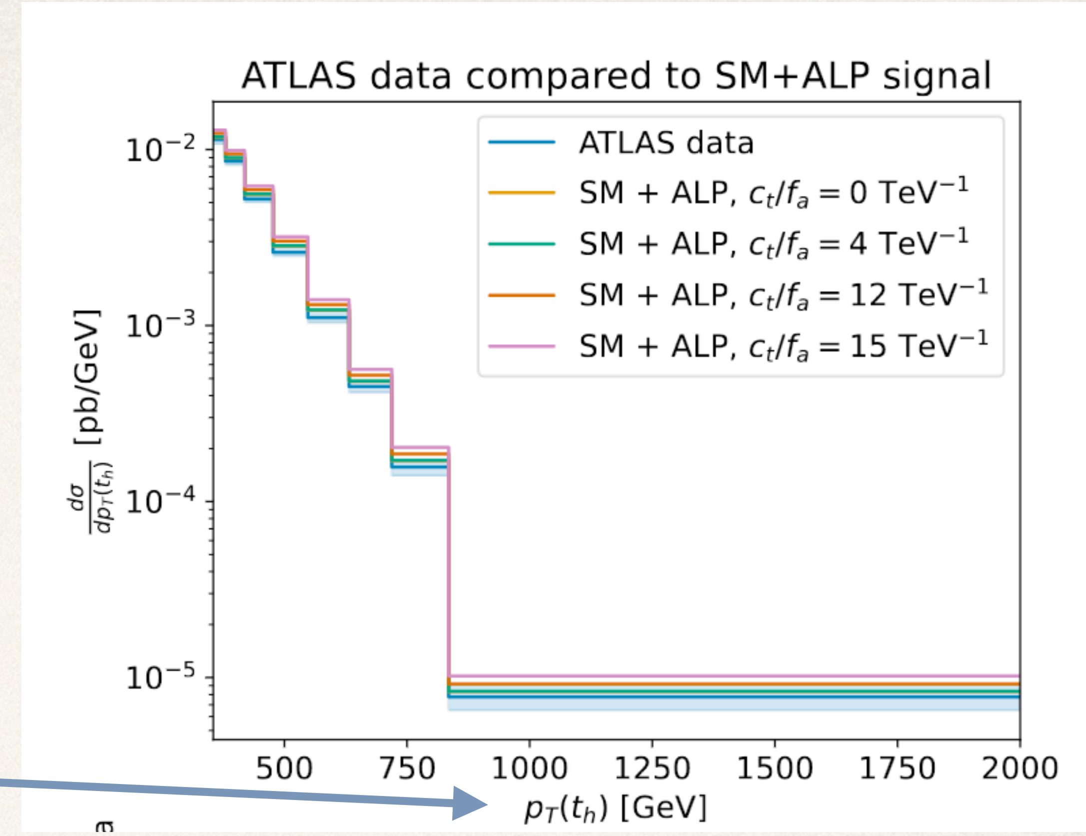


Exp limit depends on c/f = coupling/scale
Limit on f, ALP scale, should be >> m(ZZ)
—> Discussion on validity range

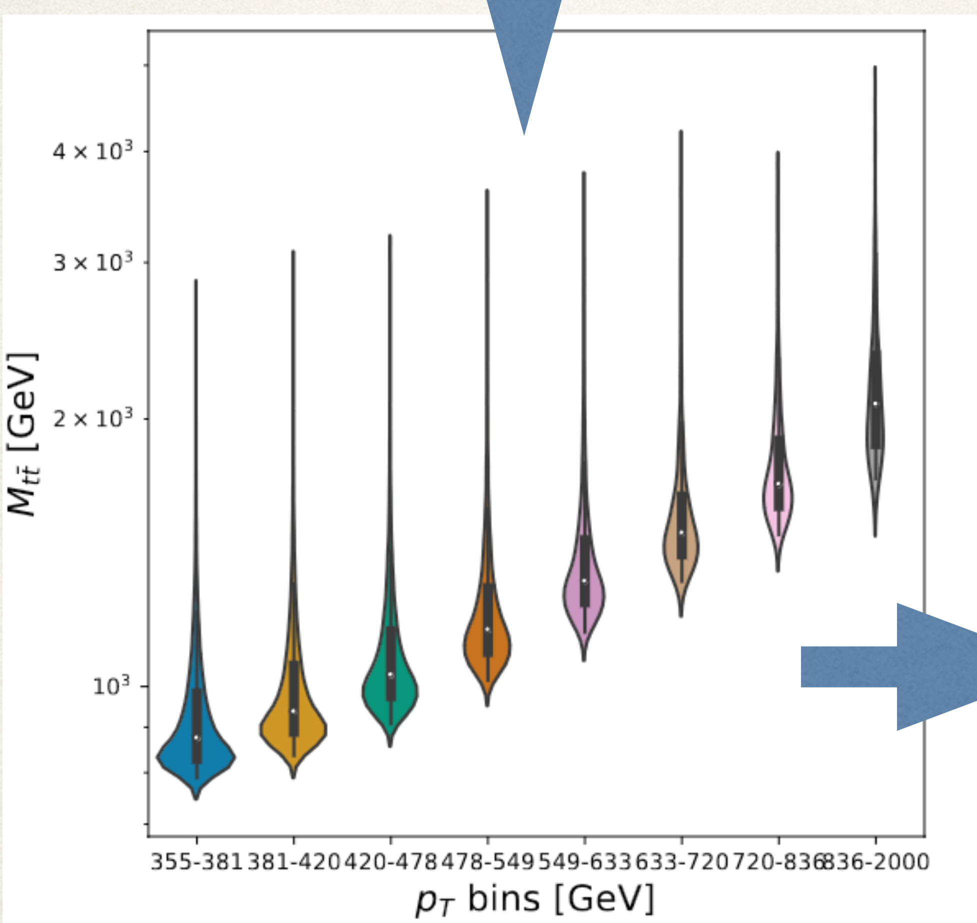
The issue of validity

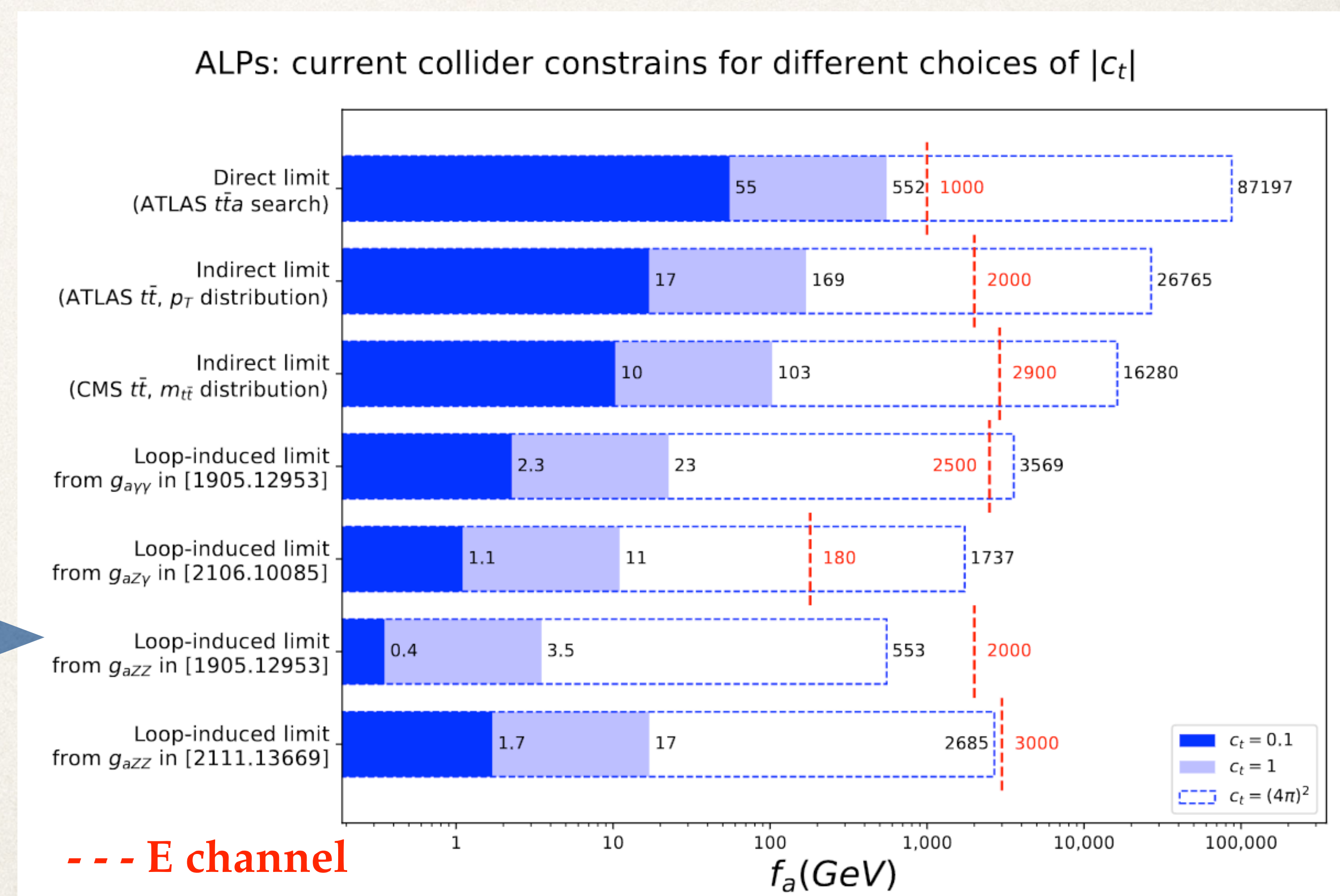
For example, for the top coupling





This observable is not directly E





Esser, Madigan, VS, Ubiali. JHEP (23)

Summary ALPs@colliders

The existence of axions, ALPs and other pseudo-GBs is a typical prediction of new strongly-coupled/extra-dimensional physics scenarios with approx symmetries

Summary ALPs@colliders

The existence of axions, ALPs and other pseudo-GBs is a typical prediction of new strongly-coupled/extra-dimensional physics scenarios with approx symmetries

Lots of efforts searching for photon-axion, electron-axion from different sources (cosmo/astro/cavities…)

Axion searches are a paradigmatic example of **complementarity**

Axions/ALP searches have been dominated by the old paradigms of the QCD axion

Summary ALPs@colliders

The existence of axions, ALPs and other pseudo-GBs is a typical prediction of new strongly-coupled/extra-dimensional physics scenarios with approx symmetries

Lots of efforts searching for photon-axion, electron-axion from different sources (cosmo/astro/cavities…)

Axion searches are a paradigmatic example of **complementarity**

Axions/ALP searches have been dominated by the old paradigms of the QCD axion

ALP coupling to SM must preserve the SM gauge structure is derivative

Collider probes are complementary to usual ALP, their edge is in MeV-TeV mass range but cover arbitrary low masses too

We can look for invisible, non-resonant and resonant ALPs

Collider probes make use of the enhanced kinematics but validity, like any other EFT, must be checked

Thank you!

Questions or comments?