On axions and ALPs

Belén Gavela
Univ. Autónoma de Madrid and IFT

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UNIVERSIDAD AUTONOMA DE MADRID

ift

H2020 elusives invisiblesPlus

We will consider the SM plus a generic scalar field a

with derivative couplings to SM particles

and free scale f_a:

an ALP (axion-like particle)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\partial_\mu a}{f_a} \times {\rm SM}^\mu$$

general effective couplings

This is shift symmetry invariant: $a \to a + \text{cte.}$ ➡ **~ Goldstone boson**

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz 2017 arXiv:1701.05379

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general effective couplings

Why?

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz 2017 arXiv:1701.05379

Is the Higgs the only (fundamental?) scalar in nature?

Or simply the first one discovered?

The spin 0 window

The SM Higgs is a ~ doublet of $SU(2)_L$

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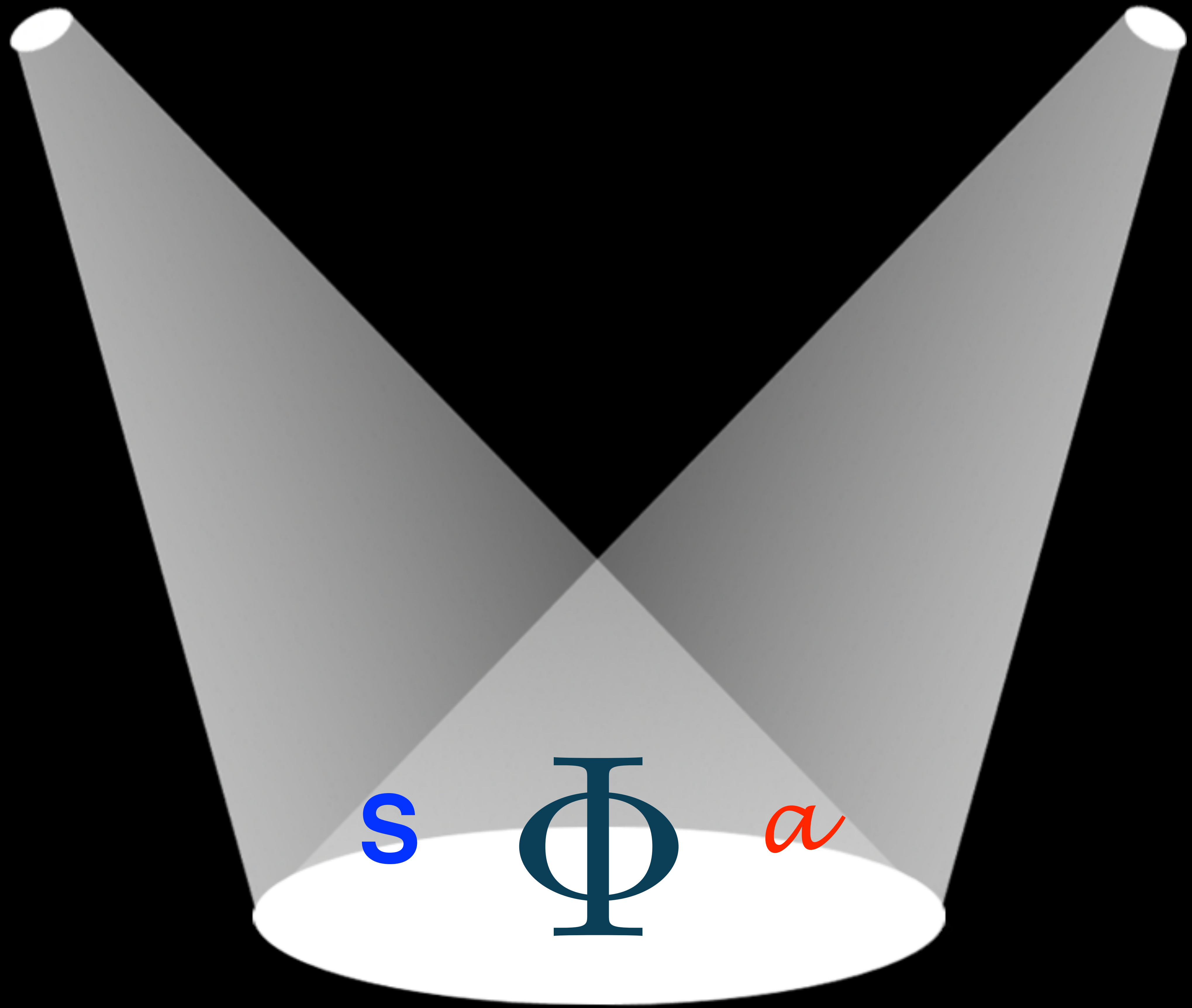
What about a singlet (pseudo) scalar?

Strong motivation from fundamental problems of the SM



Rocio del Rey

Strong motivation for singlet (pseudo)scalars from fundamental SM problems

The nature of DM is unknown

$\downarrow$

It may be a (SM singlet) scalar S

the "Higgs portal"

$$\delta\mathcal{L} = \Phi^{+}\Phi\, S^2$$

Silveira+Zee; Veltman+Yndurain; Patt+Wilczek…

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The strong CP problem

Why is the QCD θ parameter so small?

$$\mathcal{L}_{QCD} \supset \theta\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

A dynamical $U(1)_A$ solution

→ the axion a

It is a pGB: ~only derivative couplings

$$\partial_\mu a$$

Also excellent DM candidate

Peccei+Quinn; Wilczek…

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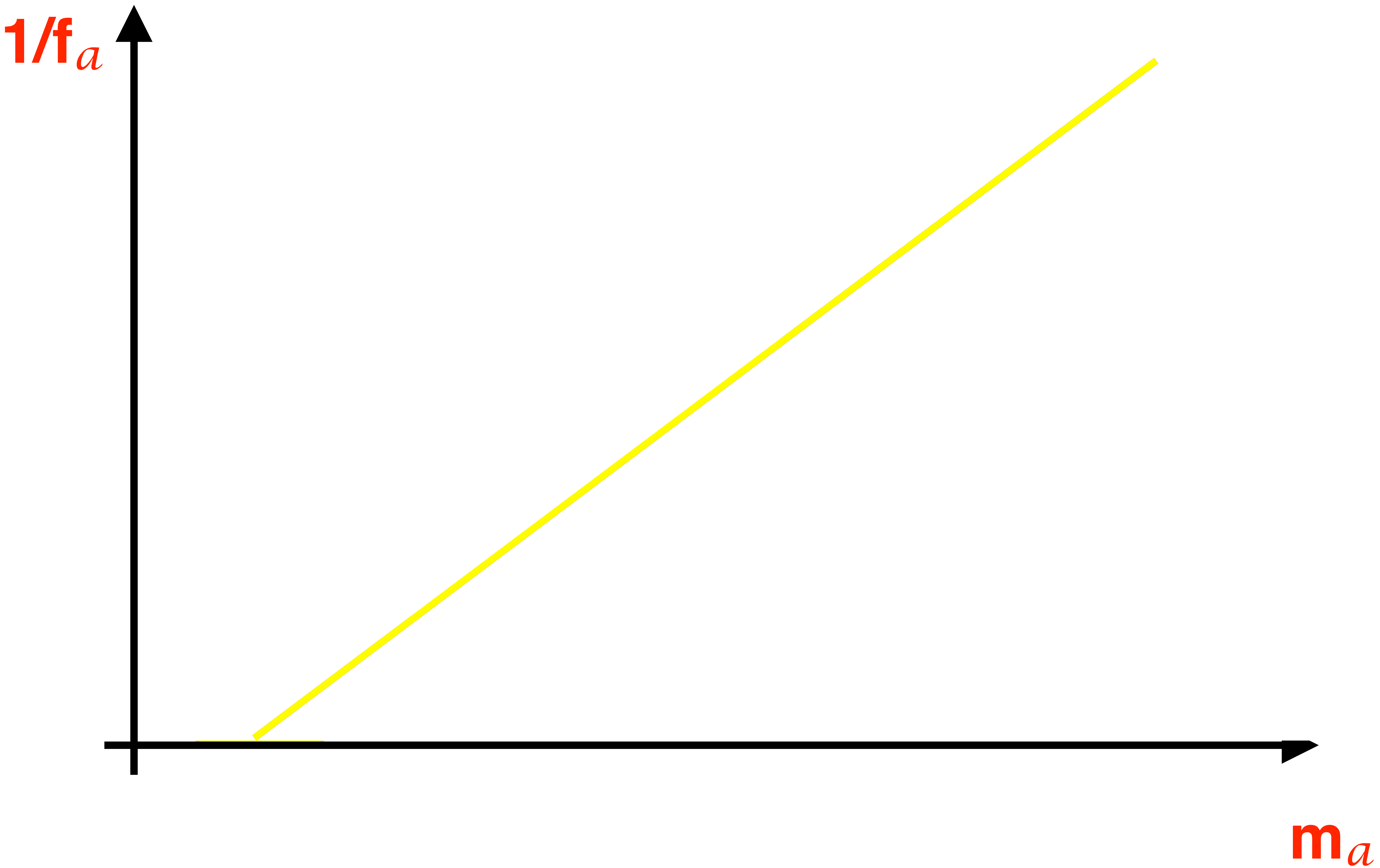

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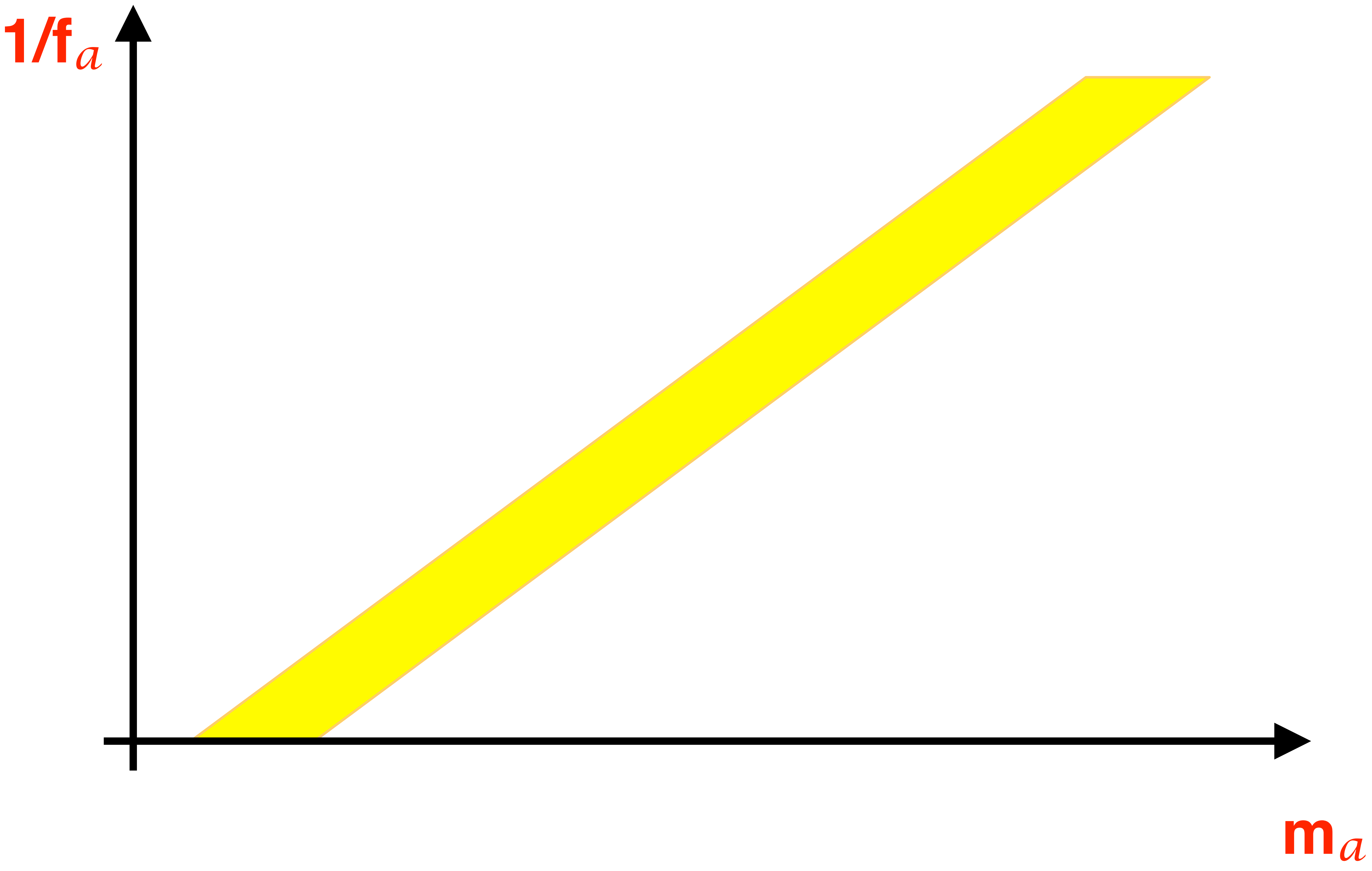

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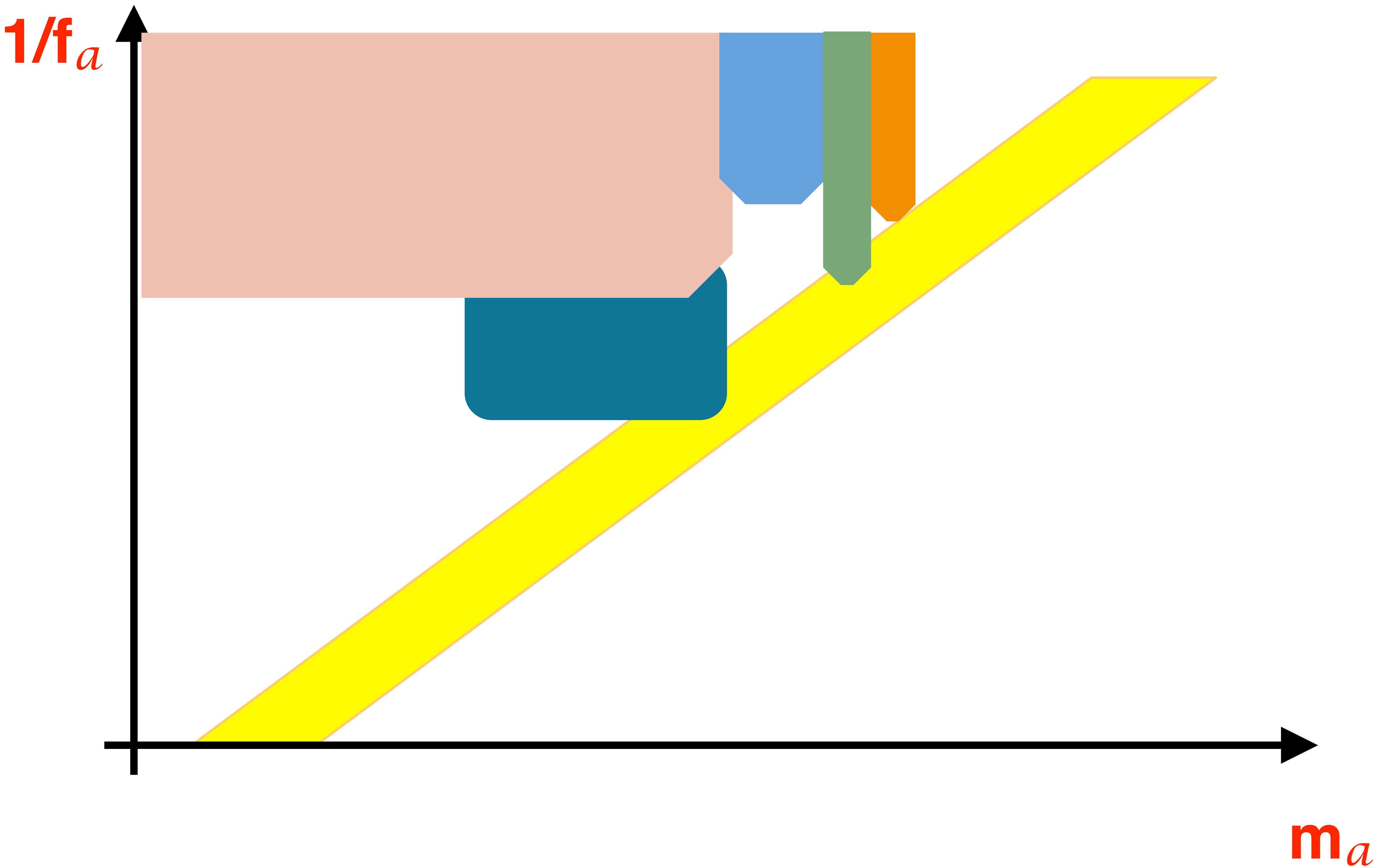

m_a vs scale f_a

$g_a \sim 1/f_a$

In QCD-like theory $m_a^2 \neq 0$ because of explicit $U(1)_A$ breaking at quantum level (instantons, Λ)

$$m_a^2 f_a^2 = \frac{\Lambda^4}{1 + \Lambda^4/(2m_q < \bar{\Psi}\Psi >)}$$

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$\Lambda \ll m_q$: Λ^4

Choi et al. 1986

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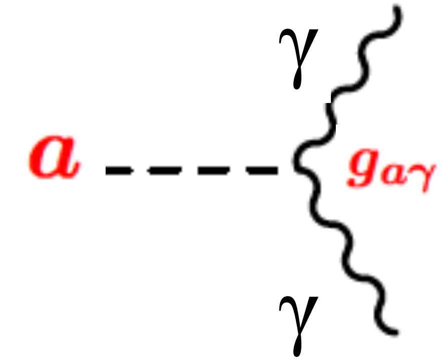
Because SN and hadronic data, if axions light enough to be emitted (and $m_a f_a$ = **cte.**)

"Invisible axion"

Intensely looked for experimentally…



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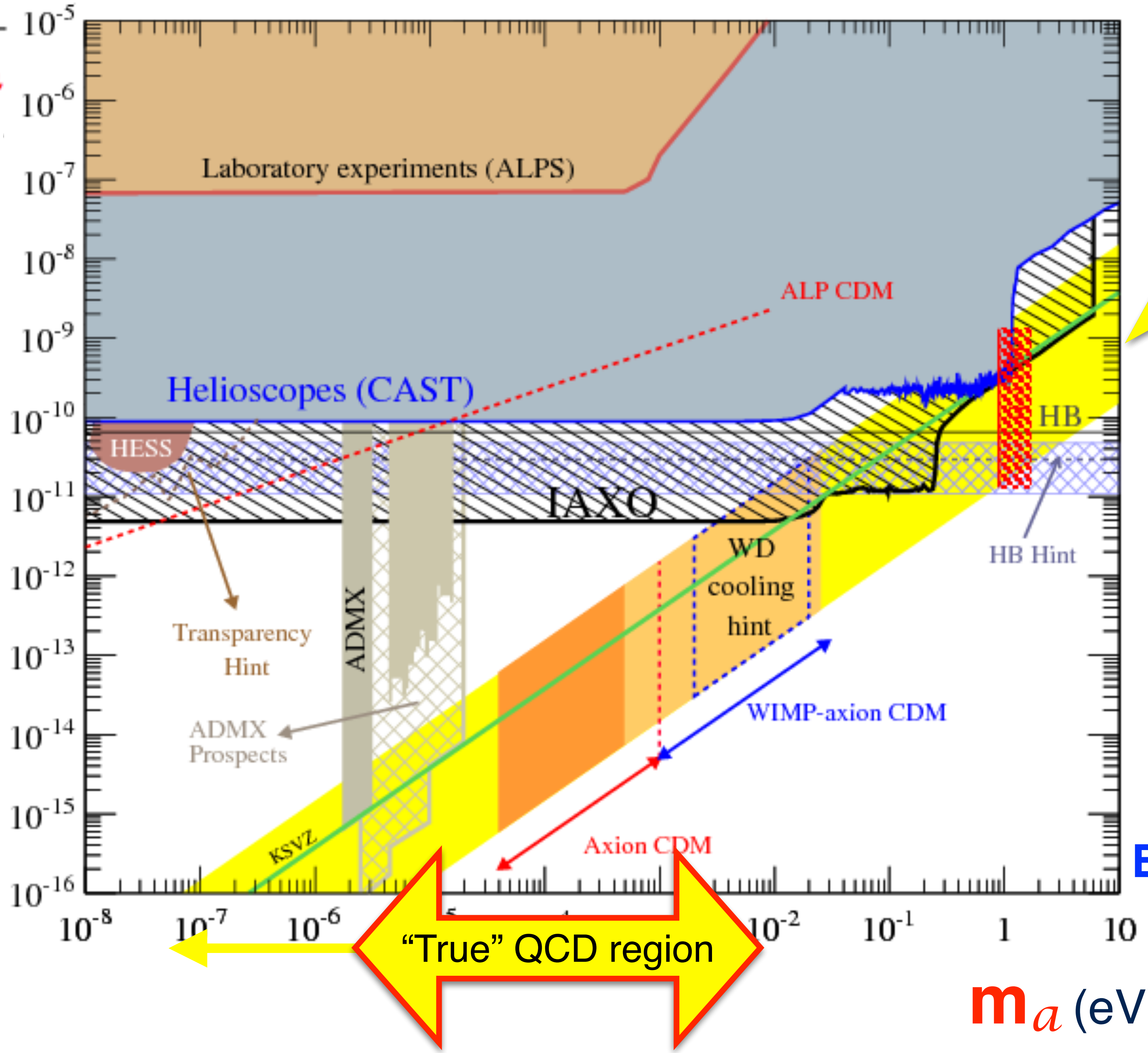
(GeV^{-1})



m_a (eV)

“True” QCD axion band

II

“Invisible axion”

e.g. KSVZ, DFSZ…

v<< f_a —>

EW hierarchy problem

… and theoretically

https://arxiv.org/pdf/1611.04652.pdf

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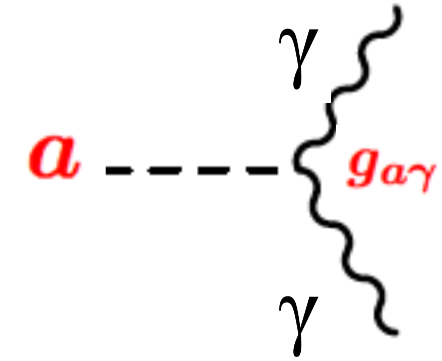

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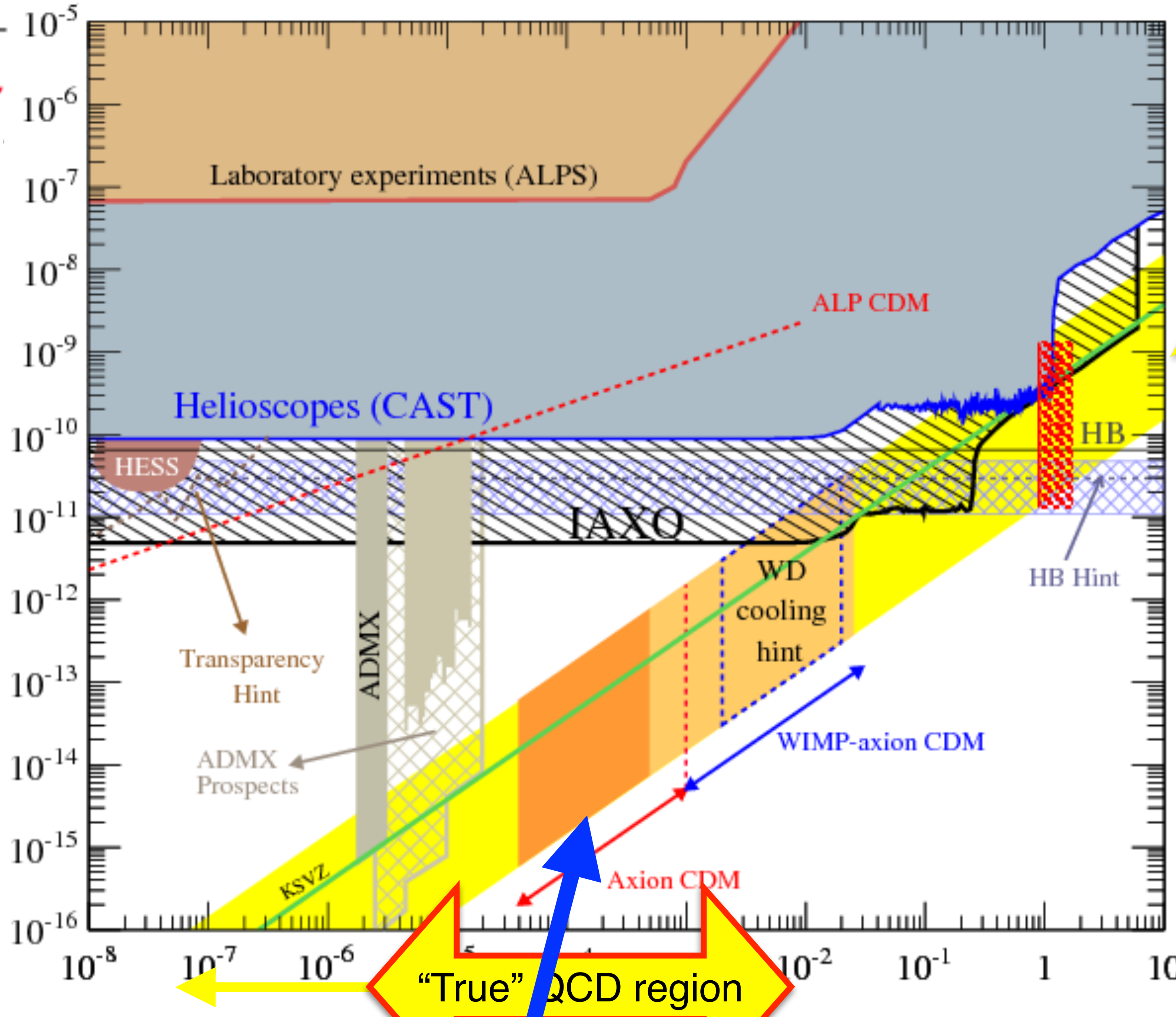

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Much activity in estimating the value of the "cte."= m_a f_a with lattice QCD. 2015: Cortona et al. ;Trunin et al.; 2016: Borsanyi et al., Petreczky et al., Taniguhi et al., Frison et al.

https://arx

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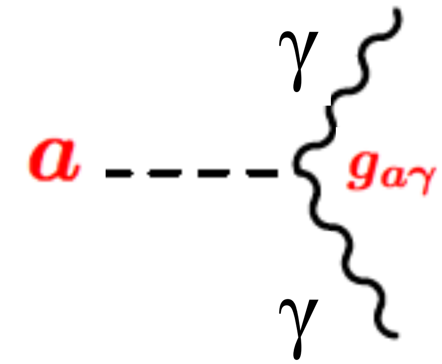

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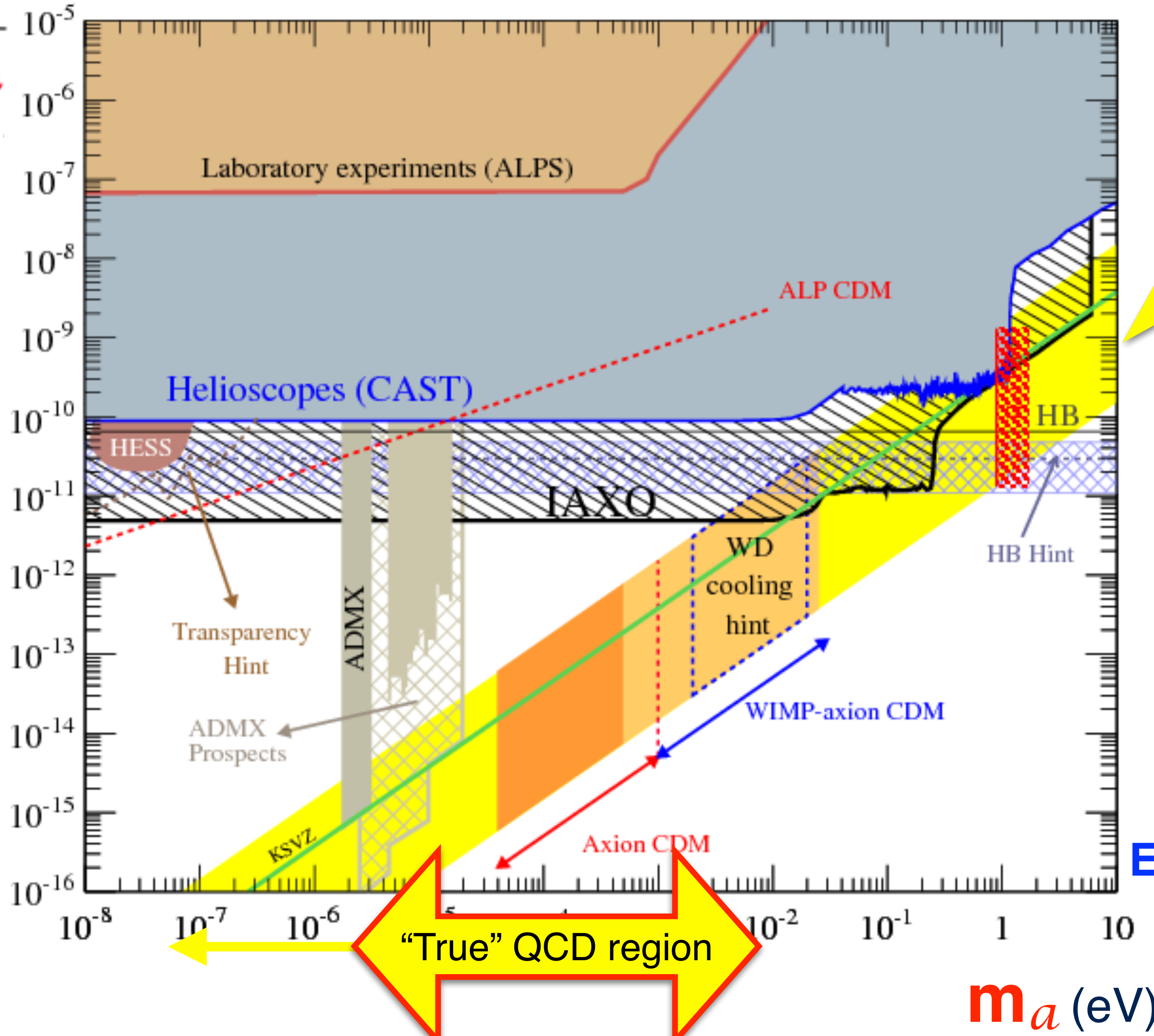

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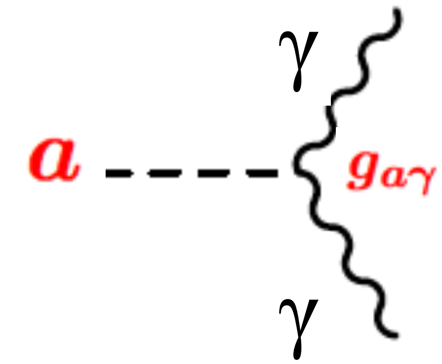

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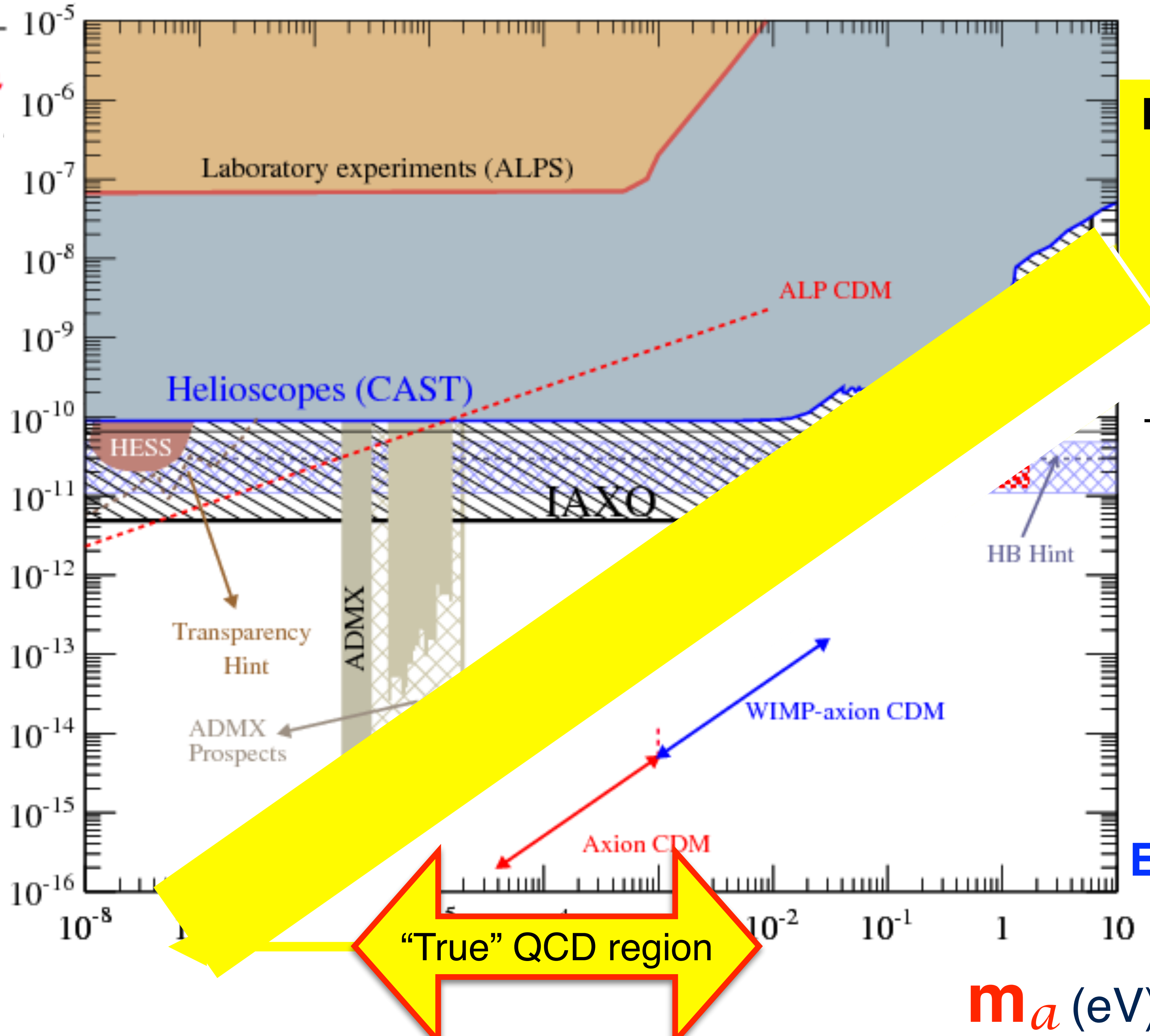

Refined KSVZ axion band: up and thinner

from Ω_{DM}
+ Landau-poles analysis

(Luzio+Mescia+Nardi 2017)

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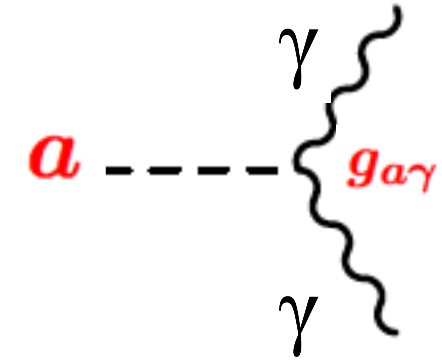

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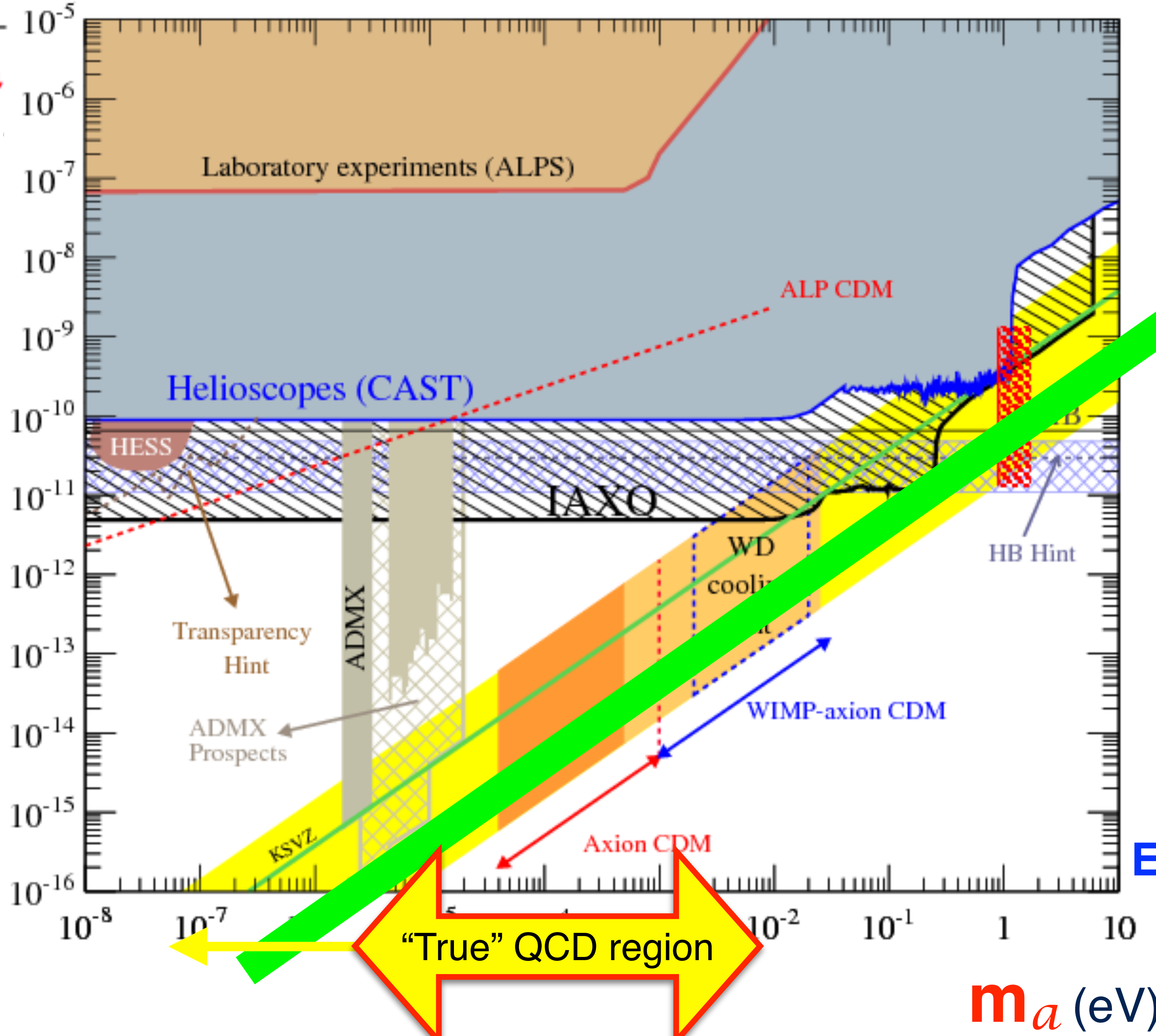

m_a (eV)

QCD axiflavon band
(creative view)

(Wilczek 82, Calibbi et al. 2016)

Identify U(1) of Peccei-Quinn with Froggat-Nielsen's

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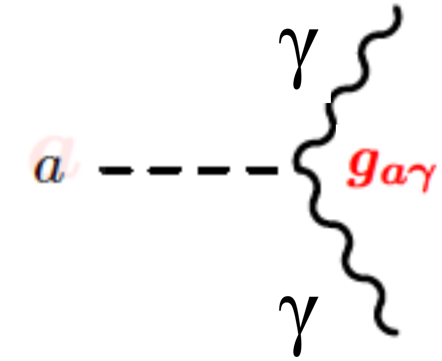

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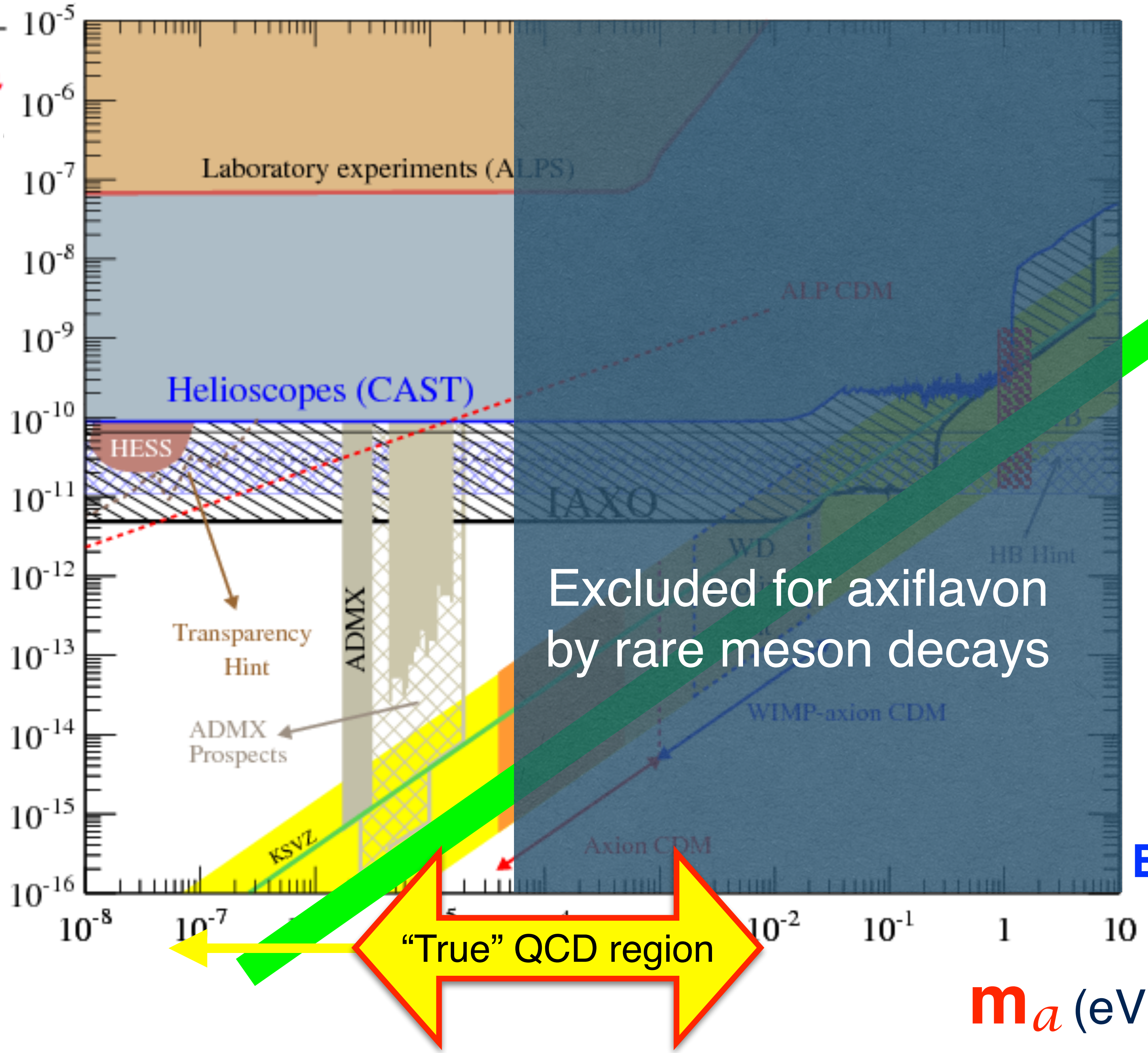

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? < m_a , f_a < ?

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relax the parameter space

Recent activity on heavy "true" axions

* **Enlarging the strong SM gauge group**, with scale **Λ'**:

Dimopoulos+Susskind 79, Tye 81… Rubakov 97…Berezhiani+Gianfagna+Gianotti 01… Hsu+Saninno 04…

surge since **2016!:** Fukuda et a. 15….Gherghetta+Nagata+Shifman, Chiang et al., Khobadize…
Hook and many collaborators, Dimopoulos et al. …

e.g. $SU(3)_c \times SU(N')$ both confining

Λ_{QCD} Λ' $\Lambda' \gg \Lambda_{QCD}$

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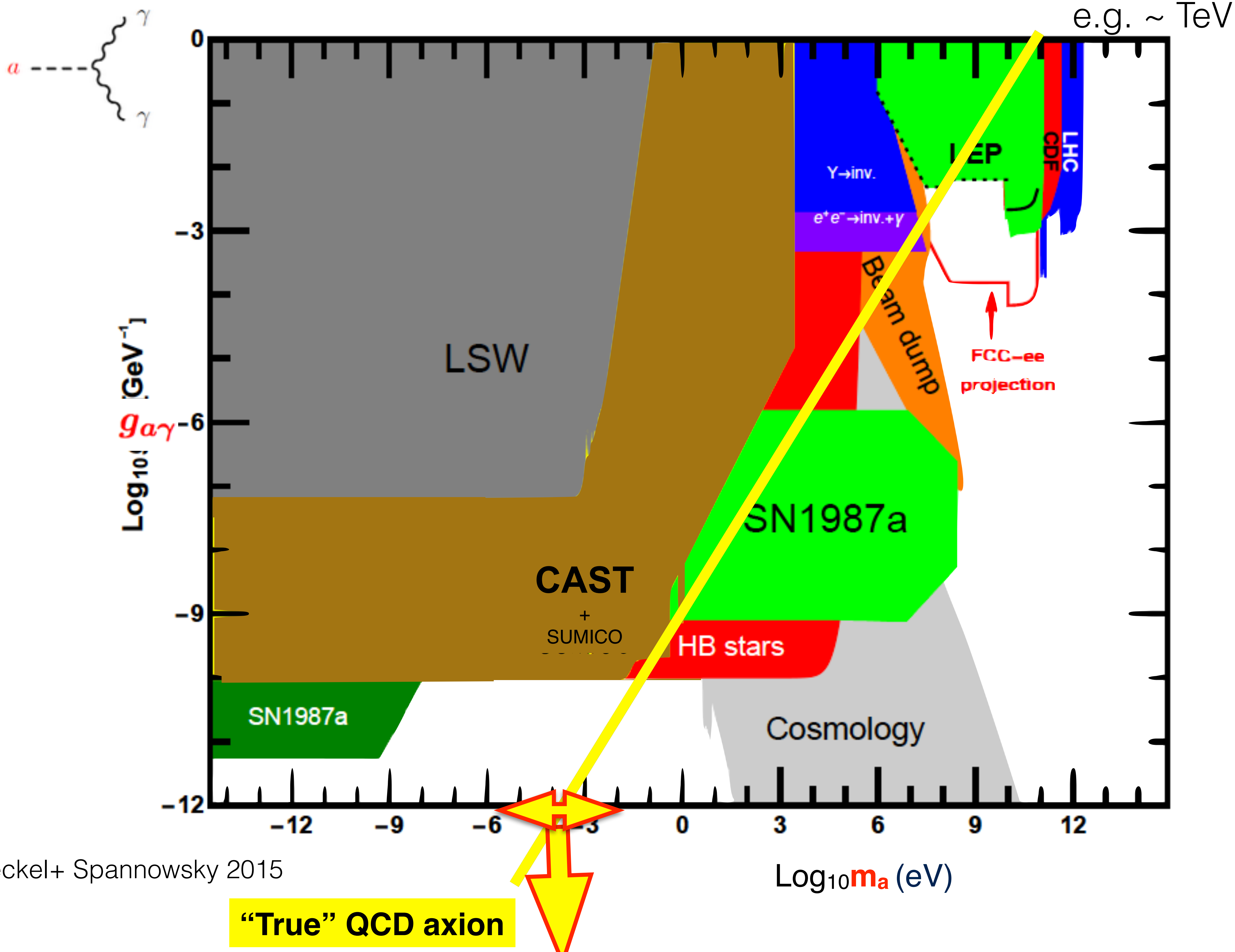
* **The ugly part: θ <u>and</u> θ'**

—>To reabsorb both : unification, and/or SM mirror world related by Z_2, or other constructions … all require tunings

Nothing works very nicely, but there is movement

—> e.g. **$f_a \sim$ TeV**, **$m_a \sim$ MeV - TeV** still solve the strong CP problem

* Much territory to explore for heavy 'true" axions and for ALPs



Jaeckel+ Spannowsky 2015

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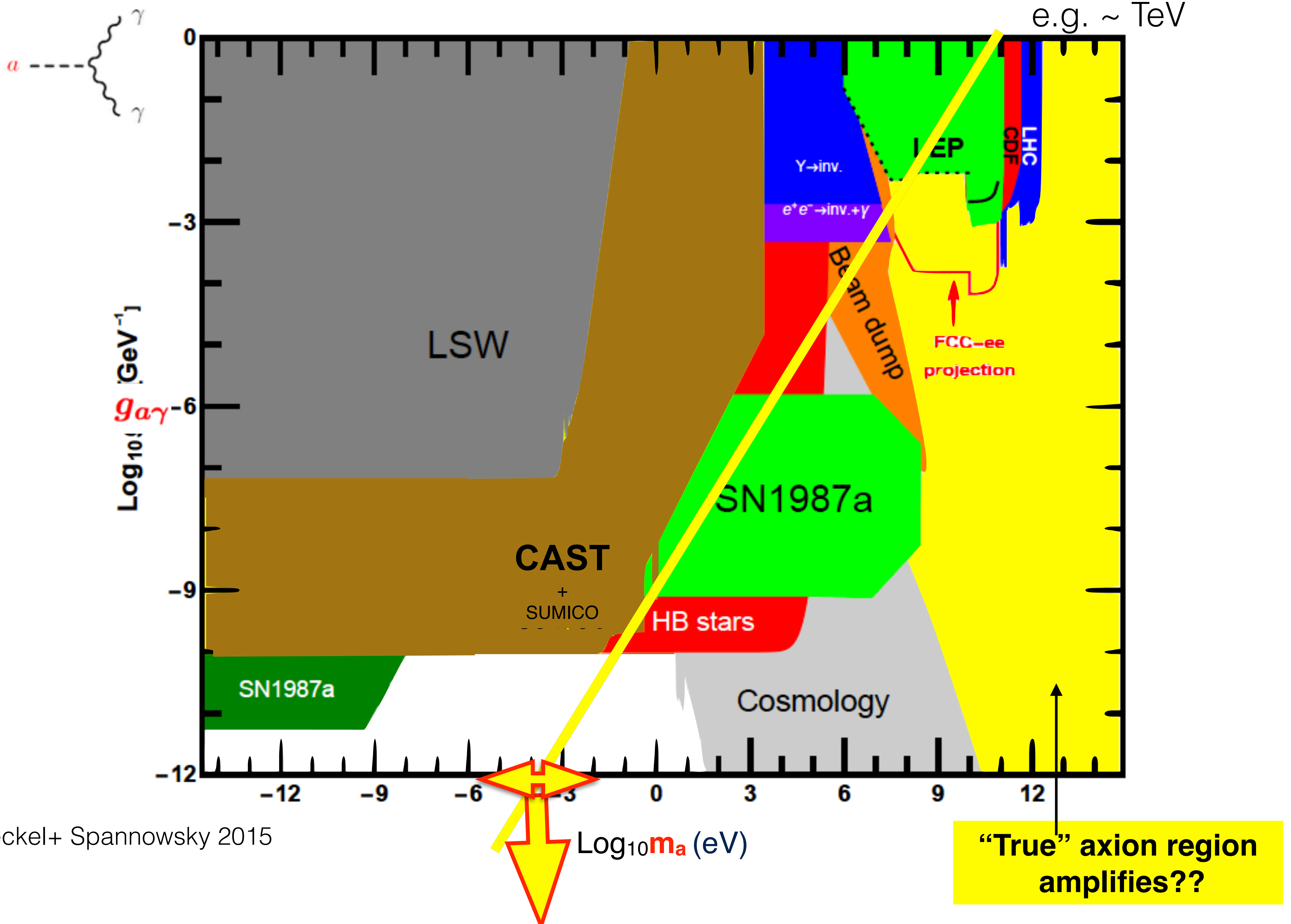

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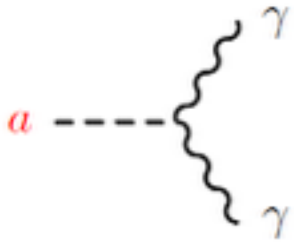
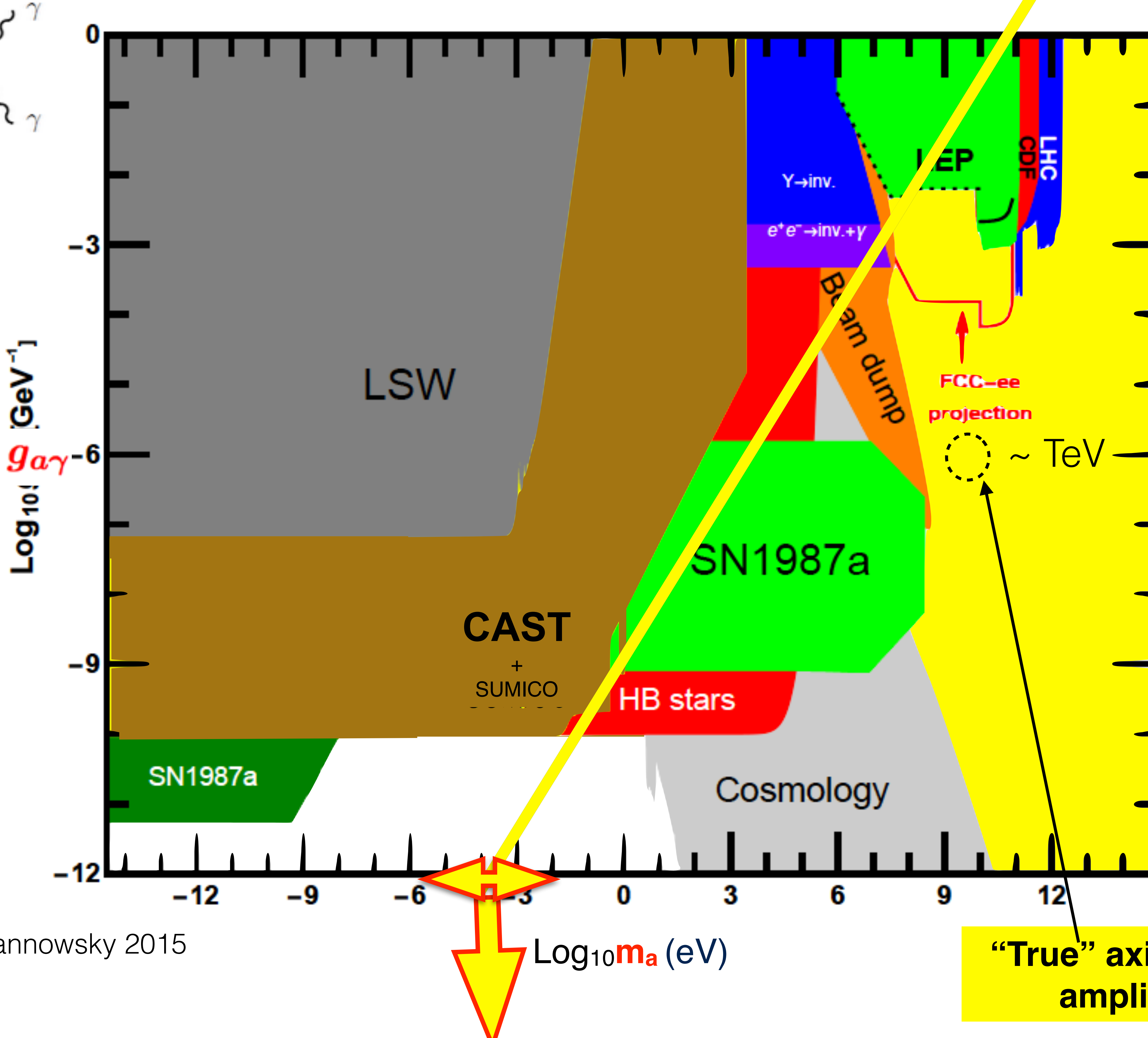


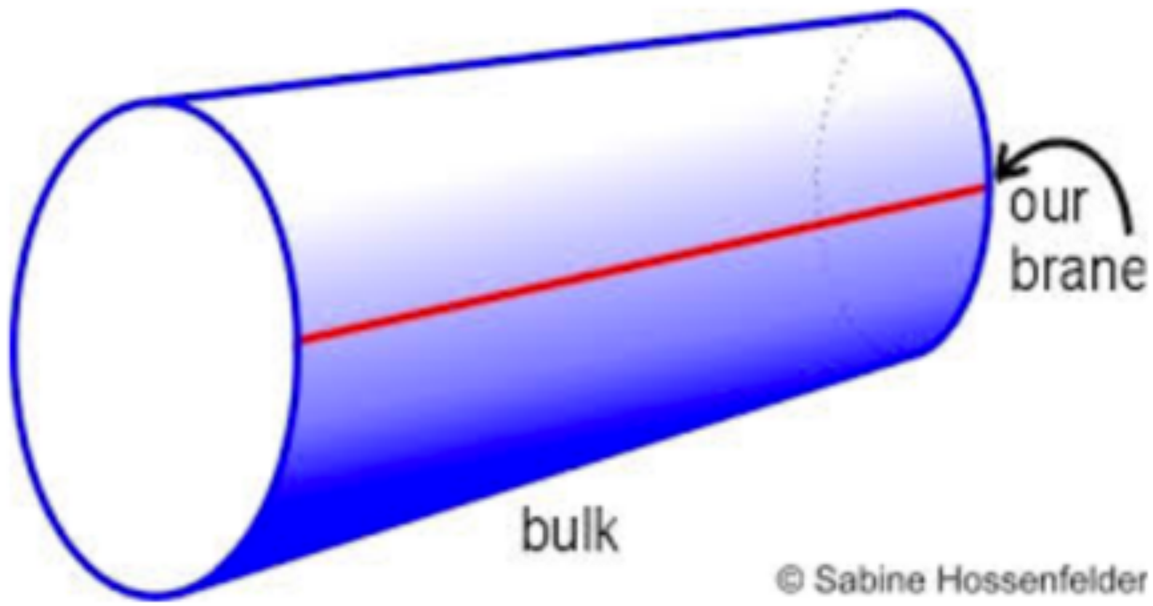


Jaeckel+ Spannowsky 2015

"True" axion region amplifies??

(Pseudo)Goldstone Bosons also in many BSM theories

* e.g. Extra-dim Kaluza-Klein: 5d gauge field compactified to 4d
  the Wilson line around the circle is a GB, which behaves as an axion in 4d



* Majorons, for dynamical neutrino masses

* From string models

* A recent example: the "relaxion" is not a GB but <u>part</u> of its couplings are purely derivative as those of ALPs, e.g. $\phi W_{\mu\nu}\tilde{W}^{\mu\nu}$ (Flacke et al. 2016)

……

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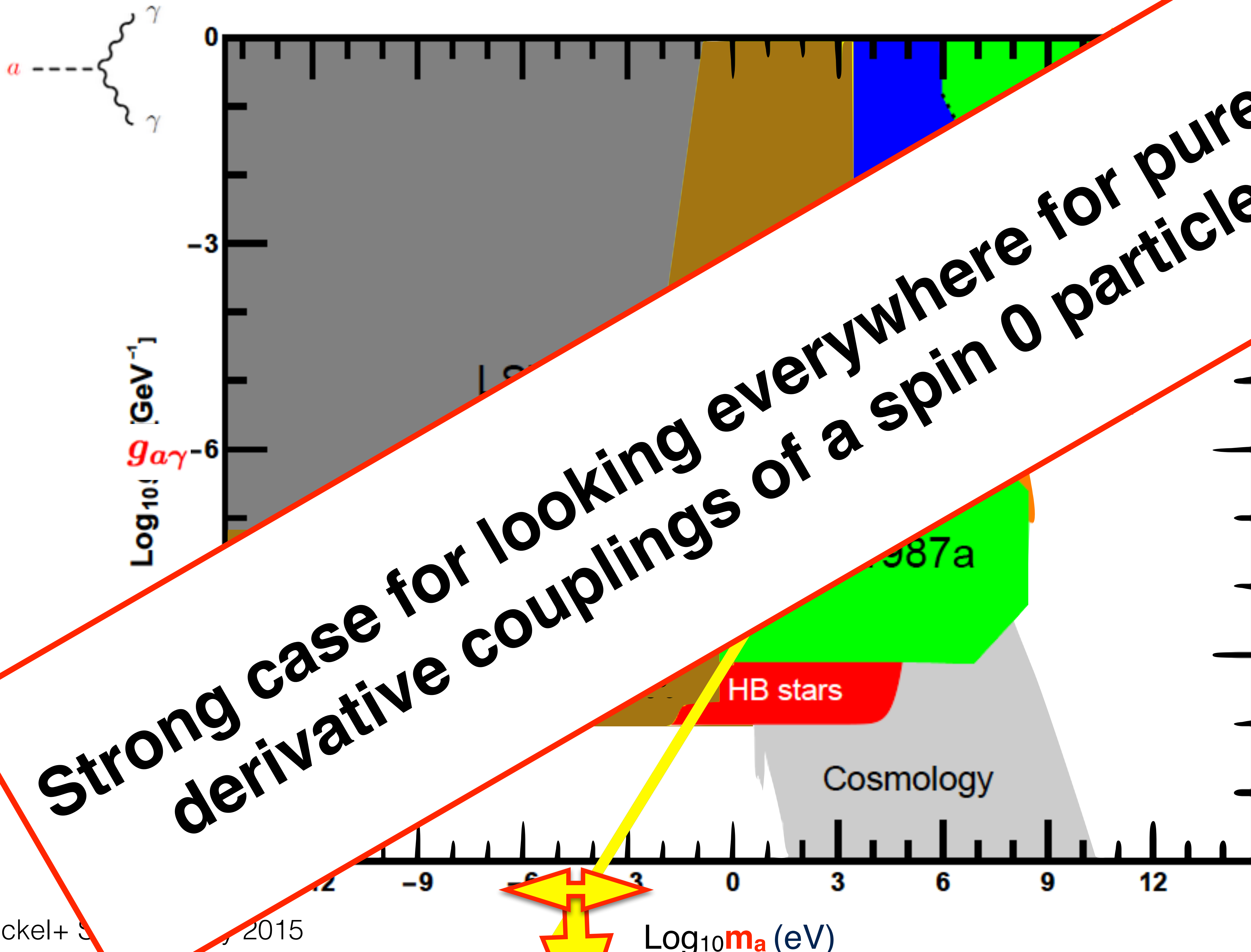

Strong case for looking everywhere for purely derivative couplings of a spin 0 particle

Jaeckel+ S… 2015

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and free scale f_a:

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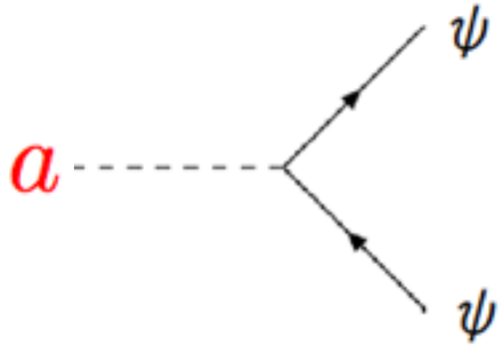
general effective couplings

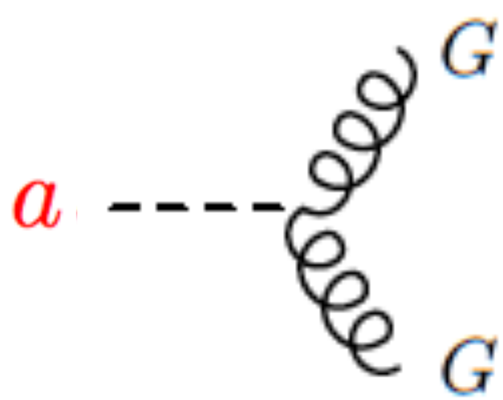
THEORY plus NEW SIGNALS at colliders

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz 2017 arXiv:1701.05379

Up to date, phenomenological studies have mostly focused on ALP couplings to fermions, gluons, and especially photons



$$\partial_\mu a\, \bar{\psi}\gamma_\mu \psi$$



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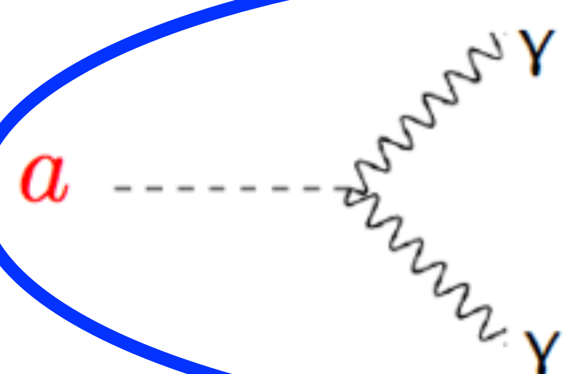
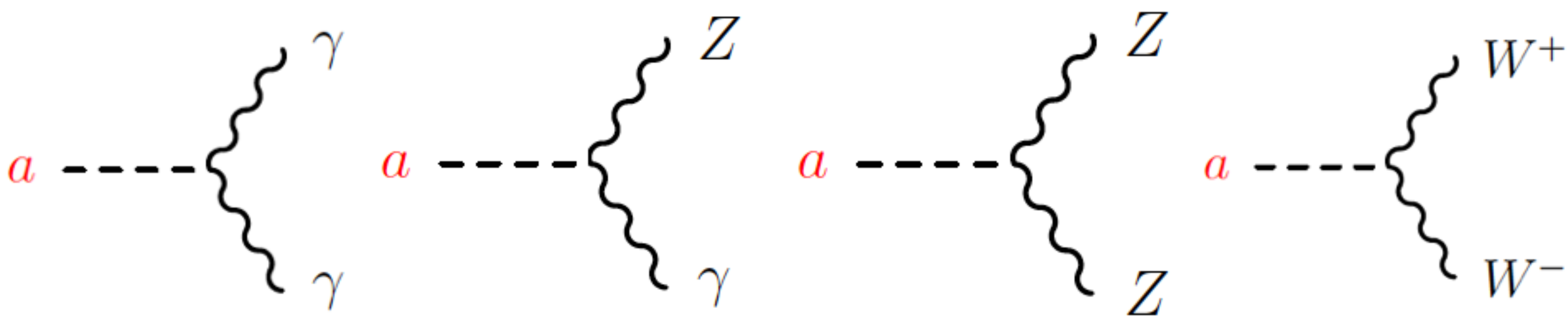


$$a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

But because of SU(2)xU(1) gauge invariance,
***a*-γγ should come together with *a*-γZ, *a*-ZZ and *a*-W^+W^- :**



+ ….

ALP-Linear effective Lagrangian at NLO

=

SM EFT

If only **bosonic** ALP-operators are considered:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\text{bosonic}} c_i \mathbf{O}_i^{d=5}$$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{a\Phi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\frac{\partial^\mu a}{f_a}$$

Georgi, Kaplan, Randall 1986

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SM EFT

If only **bosonic** ALP-operators are considered:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\text{bosonic}} c_i \mathbf{O}_i^{d=5}$$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{a\Phi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\frac{\partial^\mu a}{f_a}$$

SM higgs doublet

Georgi, Kaplan, Randall 1986

ALP-Linear effective Lagrangian at NLO

||

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Georgi, Kaplan, Randall 1986

ALP-Linear effective Lagrangian at NLO

II

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$$\Phi \to e^{ic_{a\Phi}\, a/f_a}\,\Phi$$

Georgi, Kaplan, Randall 1986

ALP-Linear effective Lagrangian at NLO

‖

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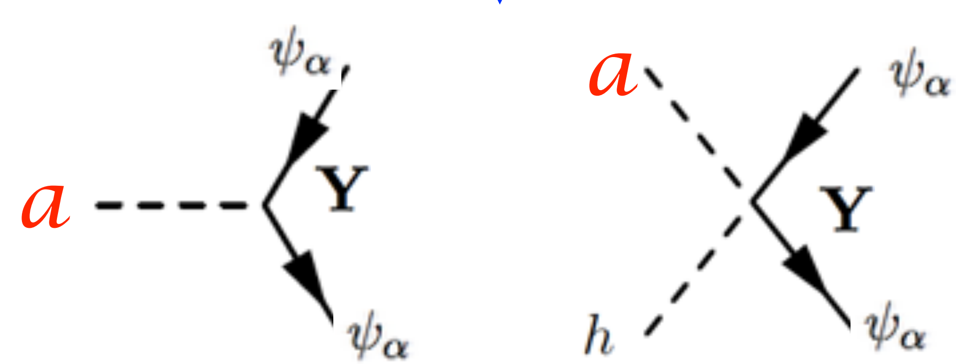

Only fermionic a-Higgs couplings

Georgi, Kaplan, Randall 1986

ALP-Linear effective Lagrangian at NLO

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Note: NO a-Higgs purely bosonic couplings

Georgi, Kaplan, Randall 1986

ALP-Linear effective Lagrangian at NLO

II

SM EFT

Complete basis (bosons+fermions):

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\text{total}} c_i \mathbf{O}_i^{d=5}$$

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$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \frac{\partial_\mu a}{f_a}\sum_{\substack{\psi=Q_L,Q_R,\\ L_L,L_R}} \bar{\psi}\gamma_\mu X_\psi \psi$$

where X_ψ is a general 3x3 matrix in flavour space

Note: NO a-Higgs bosonic couplings

Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
Salvio + Strumia + Shue, 2013

ALP-Linear effective Lagrangian at NLO

Complete basis (bosons+fermions):

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\text{total}} c_i \mathbf{O}^{d}$$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a}$$

$$f_a$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}$$

$$\bar{\psi}\gamma_\mu X_\psi \psi$$

$$=Q_L, Q_R, L_L, L_R$$

analysis parameters: $\dfrac{c_i}{f_a}$

where X_ψ is a general 3x3 matrix in flavour space

e: NO a-Higgs bosonic couplings

Georgi + Kaplan + Randall 1986
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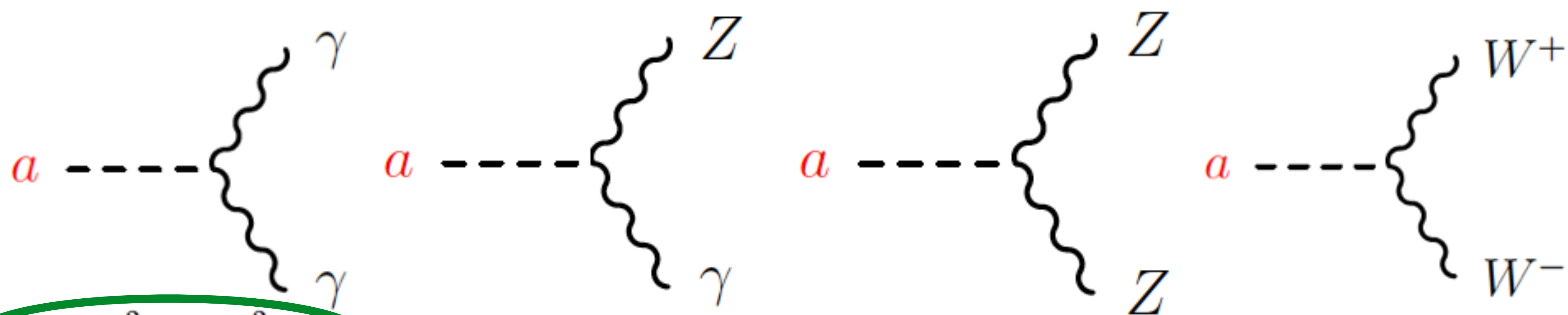
where X_ψ is a general 3x3 matrix in flavour space

contain a-γγ and other couplings

Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
Salvio + Strumia + Shue, 2013

Because of SU(2)xU(1) gauge invariance, a-γγ comes together with a-γZ, a-ZZ and a-W^+W^- :

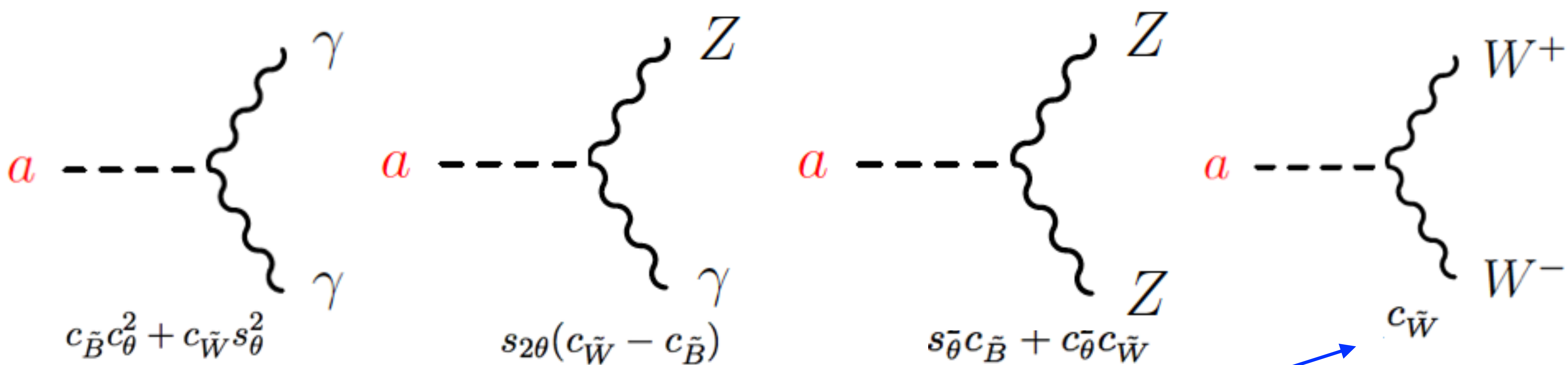


$c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2$

a-γγ studies only bounds this combination of couplings

90% CL: $|c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2| \lesssim \begin{array}{ll} 0.0025\ (f_a/\mathrm{TeV}) & m_a \leq 1\,\mathrm{MeV} \\ 2.5 \cdot 10^{-8}\ (f_a/\mathrm{TeV}) & m_a \leq 1\,\mathrm{keV} \end{array}$

Because of SU(2)xU(1) gauge invariance,
a-γγ comes together with *a*-γZ, *a*-ZZ and *a*-W⁺W⁻ :



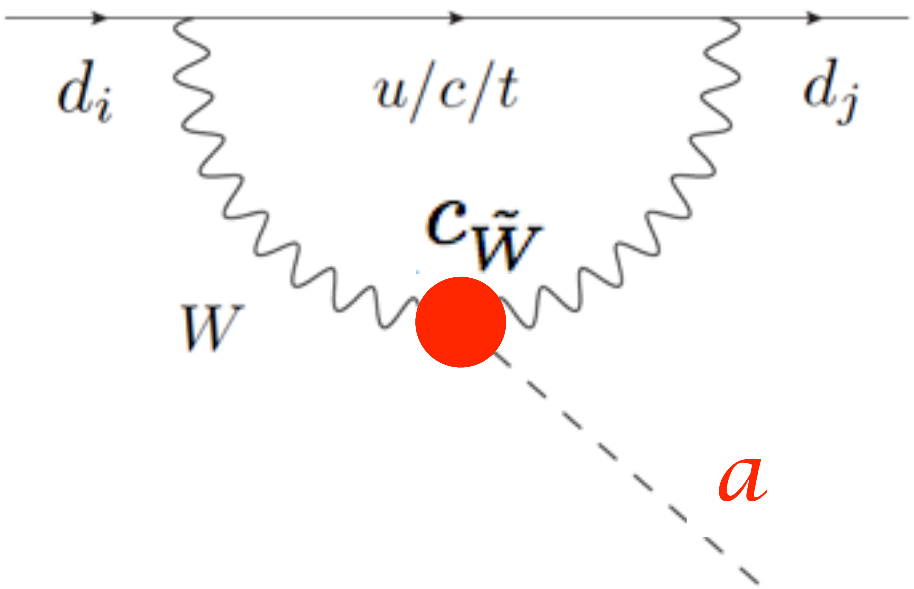
Largely disregarded up to very very recently

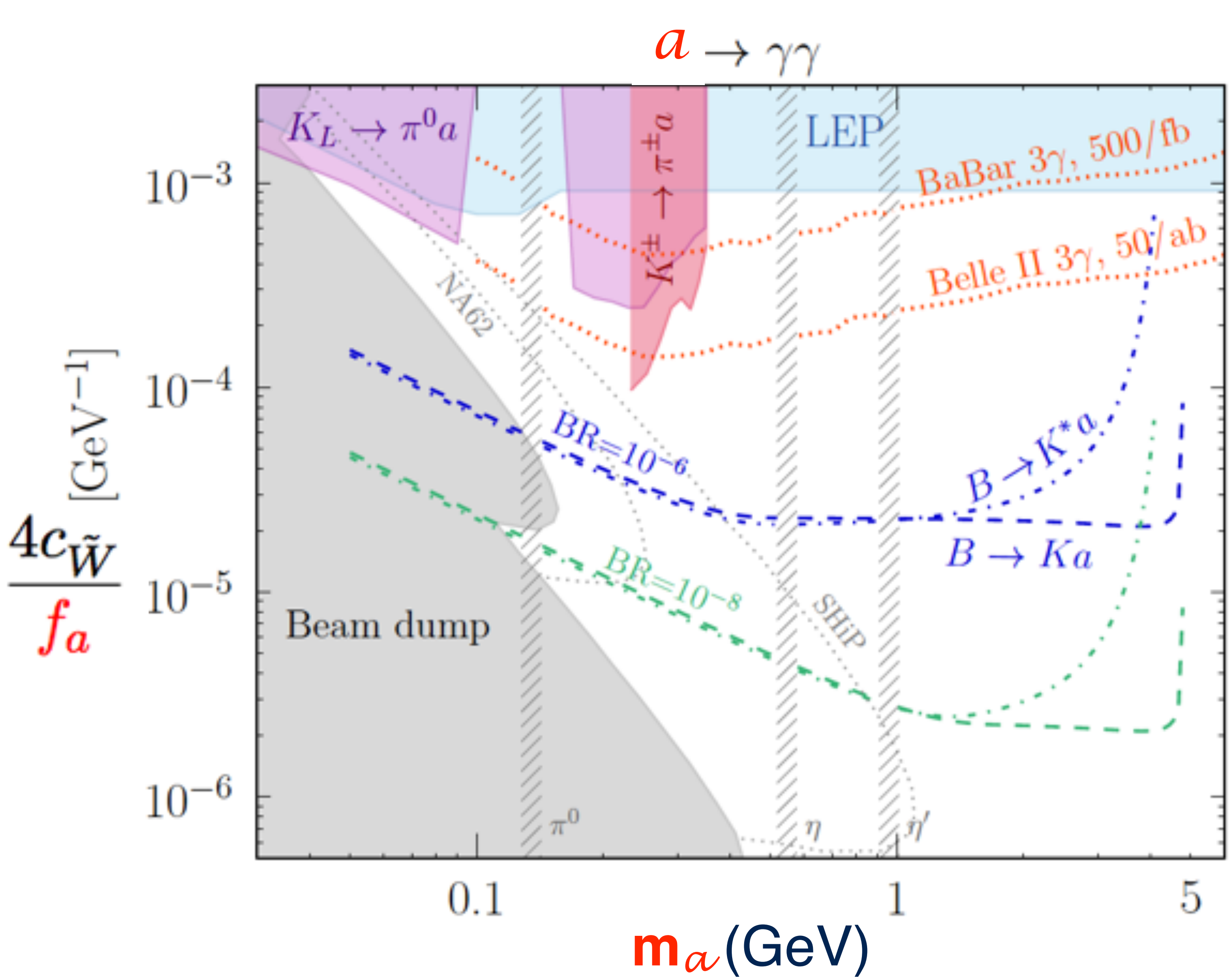
only a tiny bit in Jaeckel+Spannowsky 2015

Interesting very recent development:

$c_{\tilde{W}}$ from rare meson decays

B —> K a , K—>π a….. a —>γγ





Izaguirre+Lin+Shuve 2016

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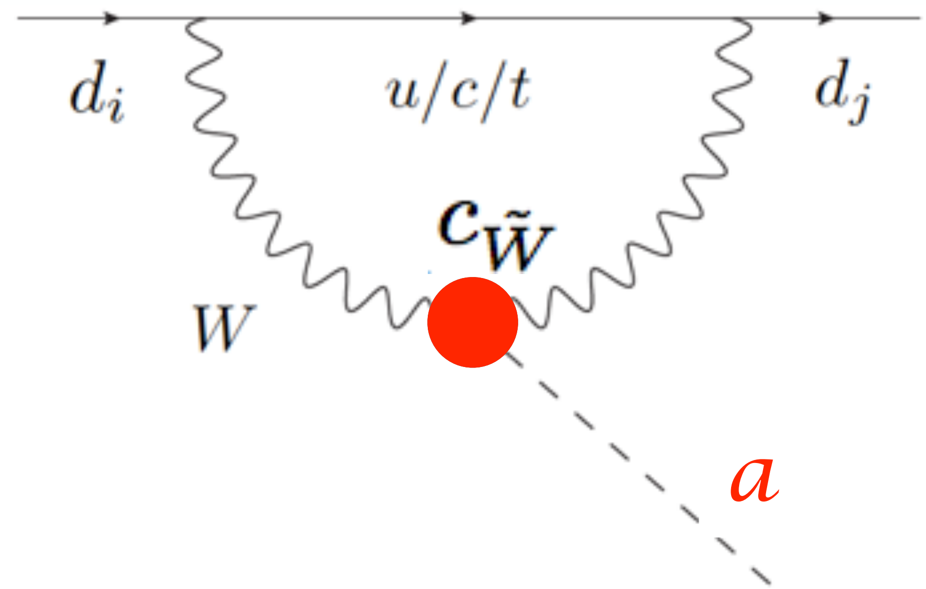
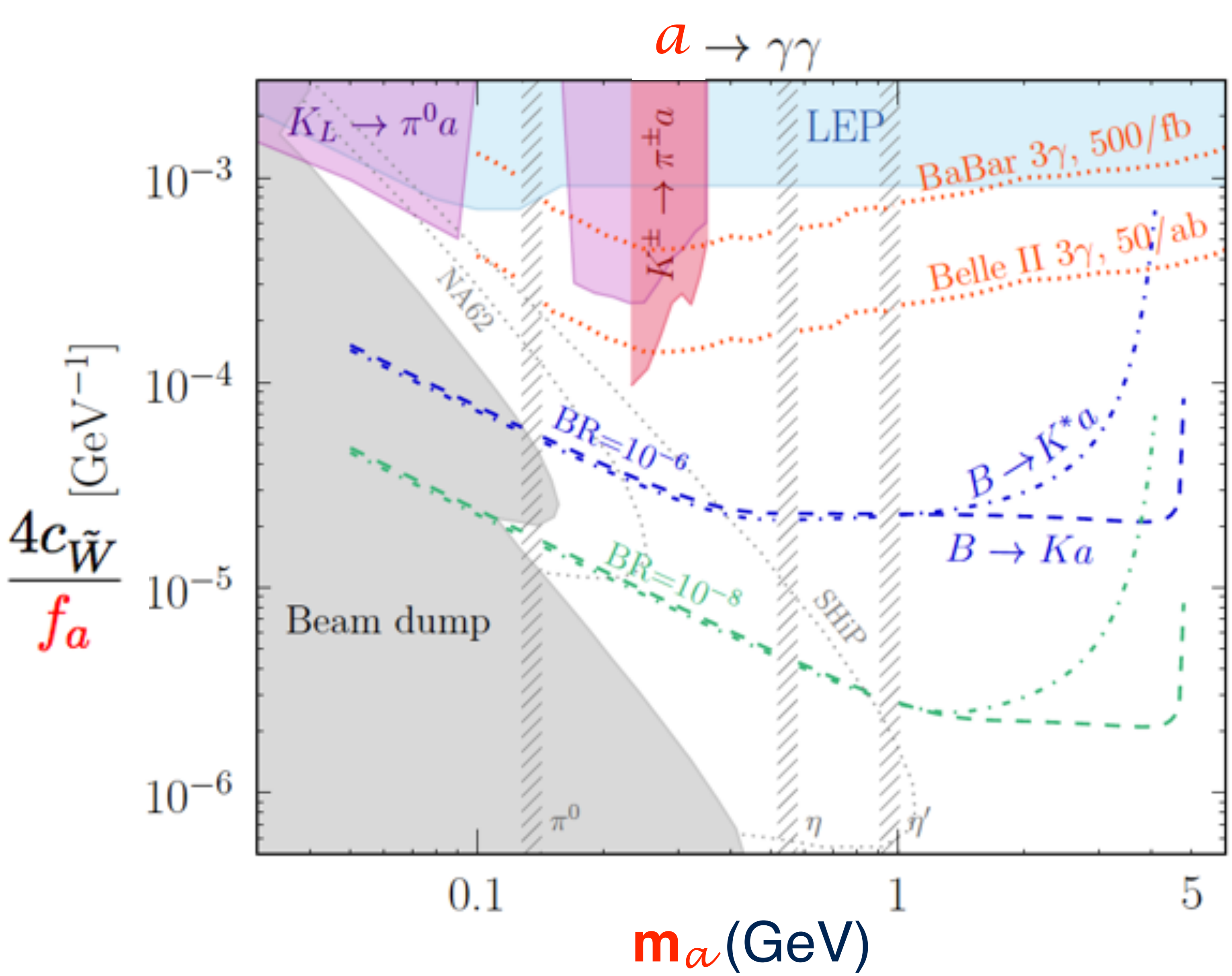
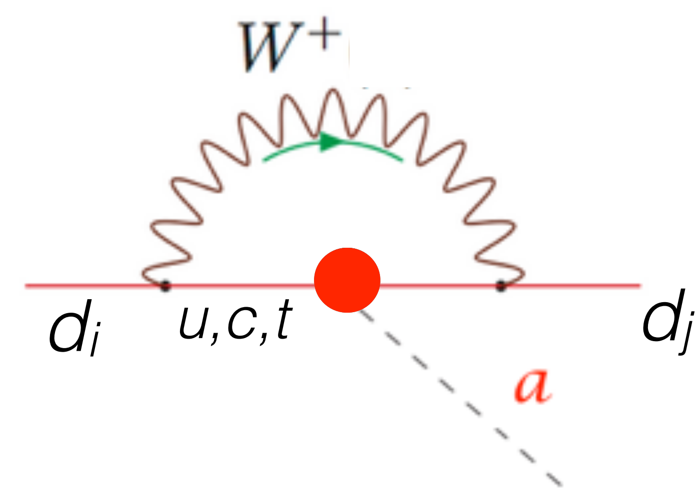




Izaguirre+Lin+Shuve 2016

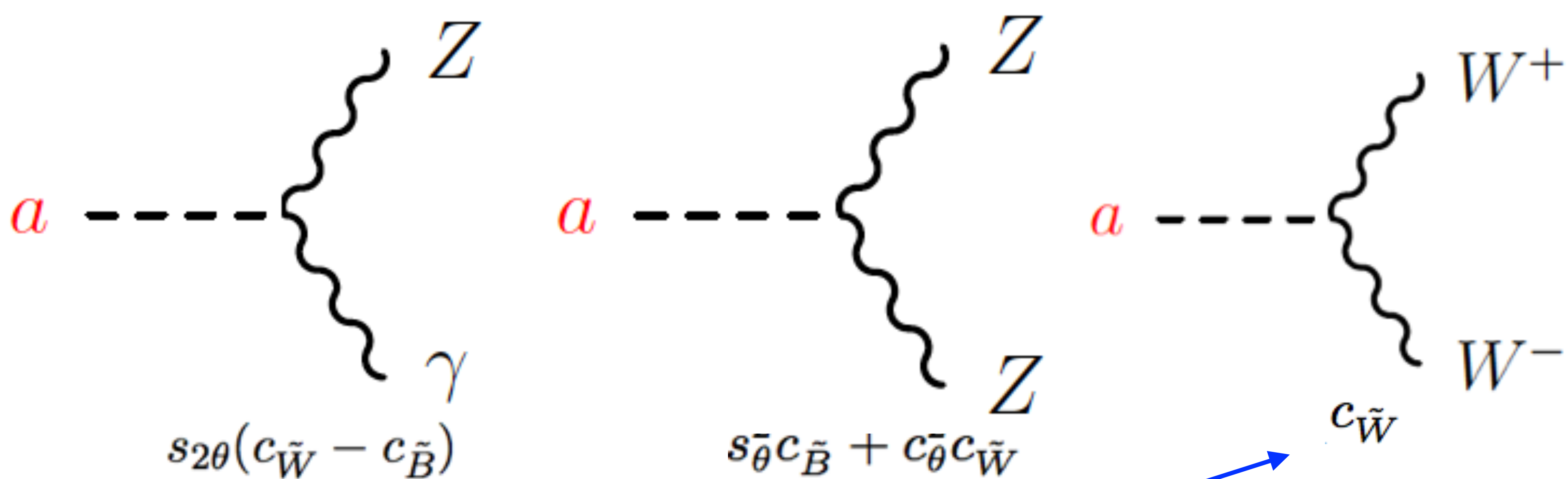
But several ops. may contribute:

$$\{c_{\tilde{W}}, c_{a\Phi}, c_{\psi_i}\}$$



+Del Rey et al. in preparation

We analyzed the impact at LEP, LHC and HL-LHC of bosonic effective a-SM couplings:



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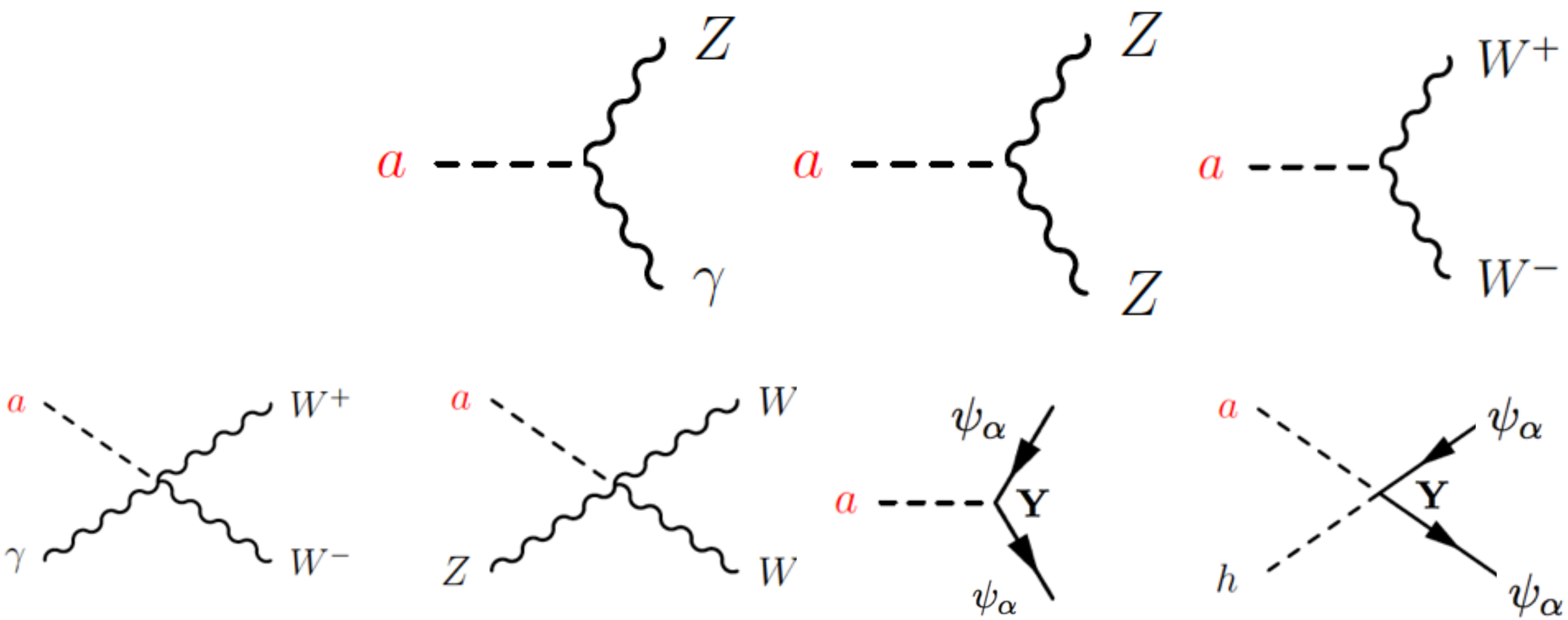
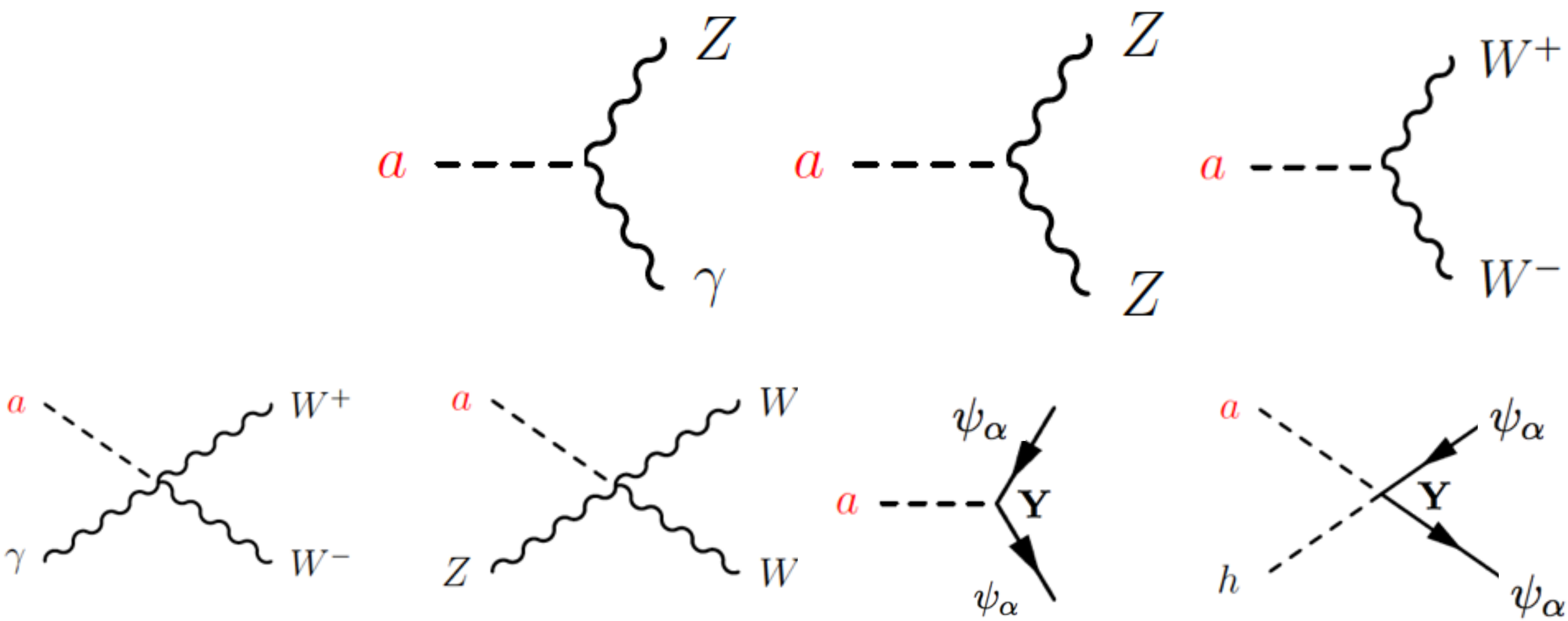


We analyzed the impact at LEP, LHC and HL-LHC of bosonic effective a-SM couplings:

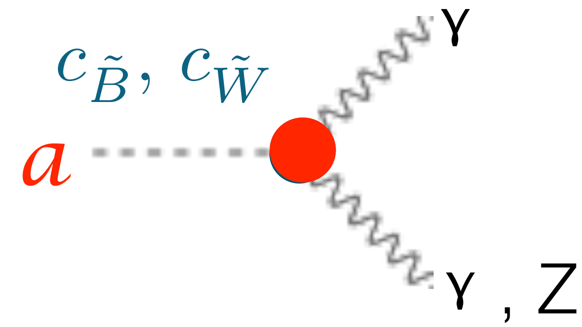
New signals: mono-Z, mono-W, associated aWγ, $at\bar{t}$



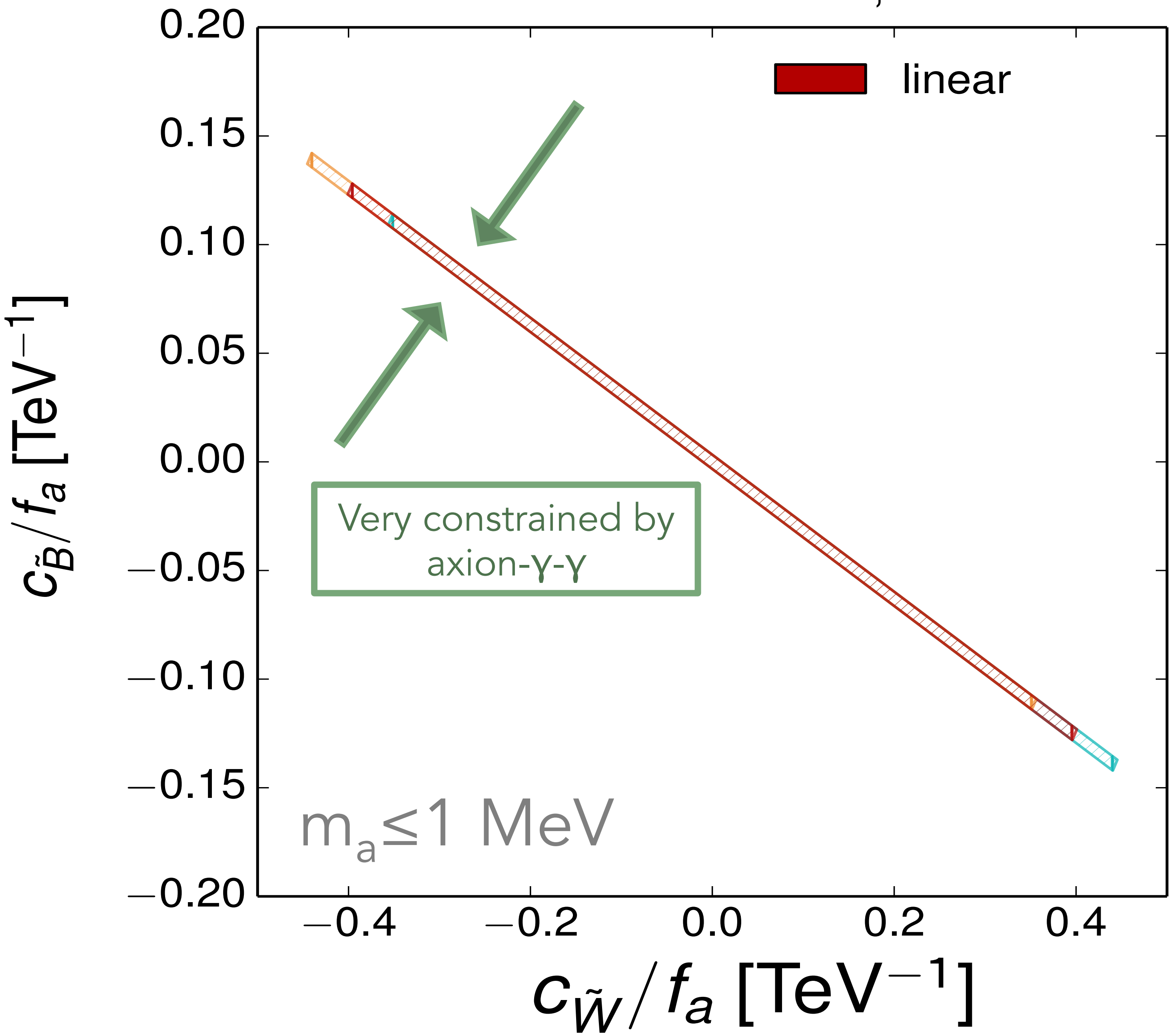
Accelerator constraints on a-γ-γ and a-γ-Z

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a}$$



LEP impact



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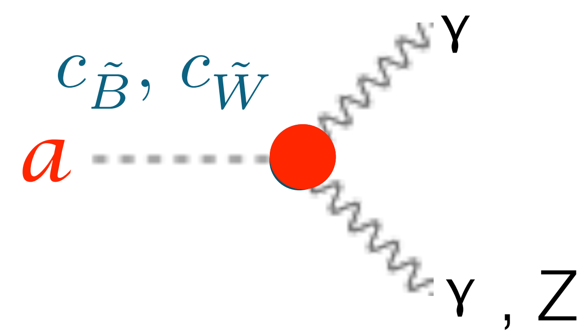
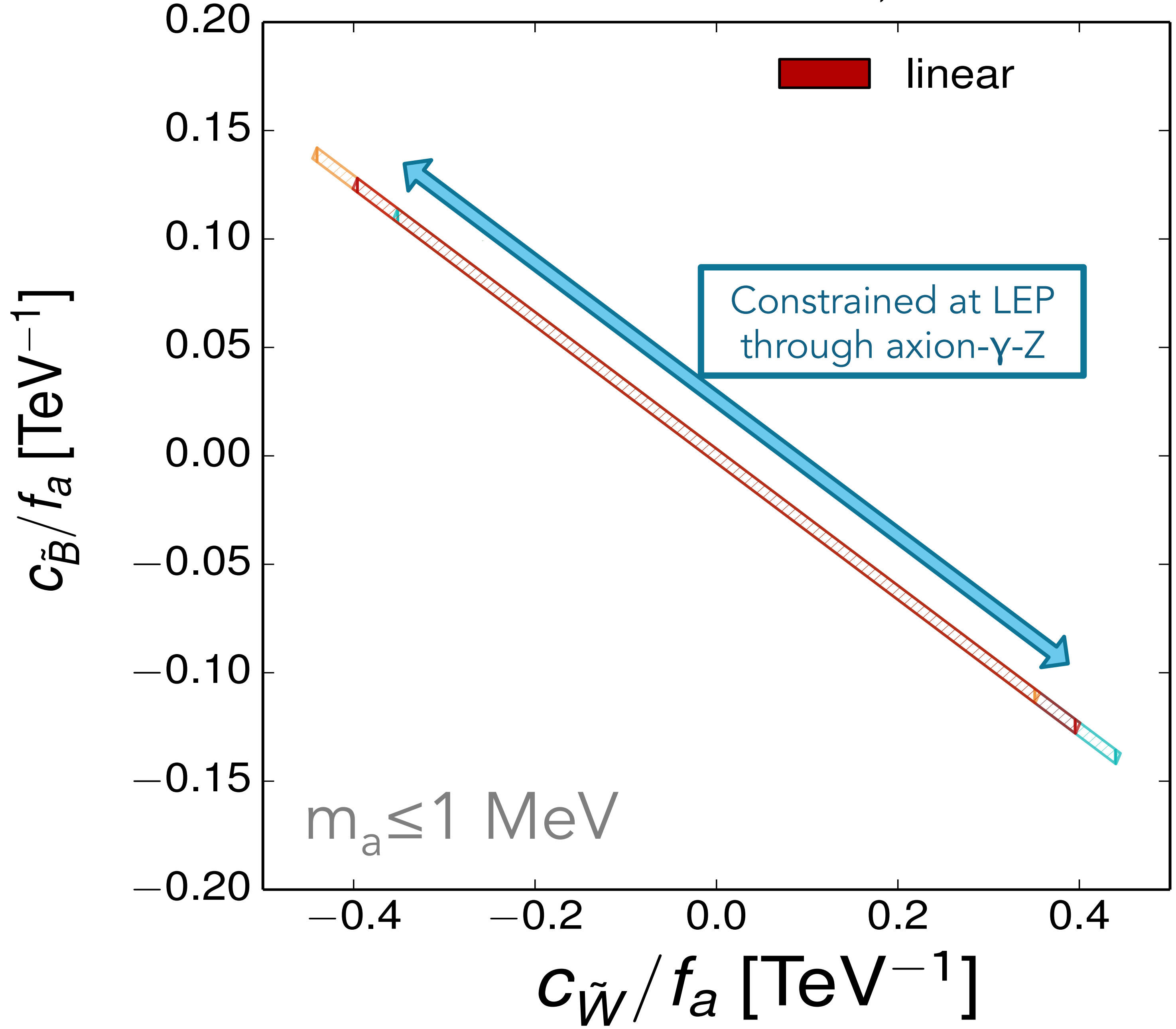


LEP impact

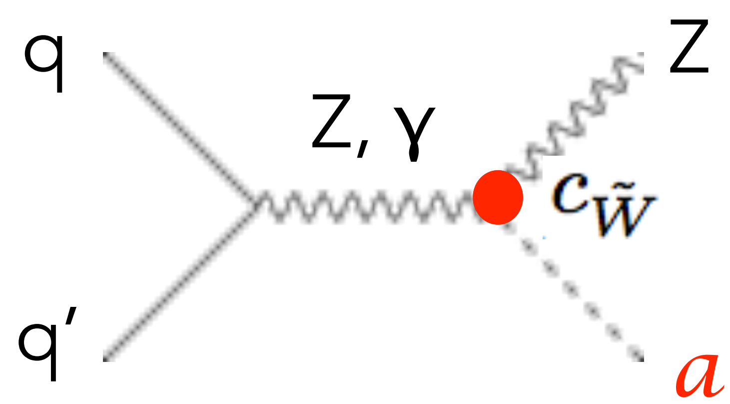


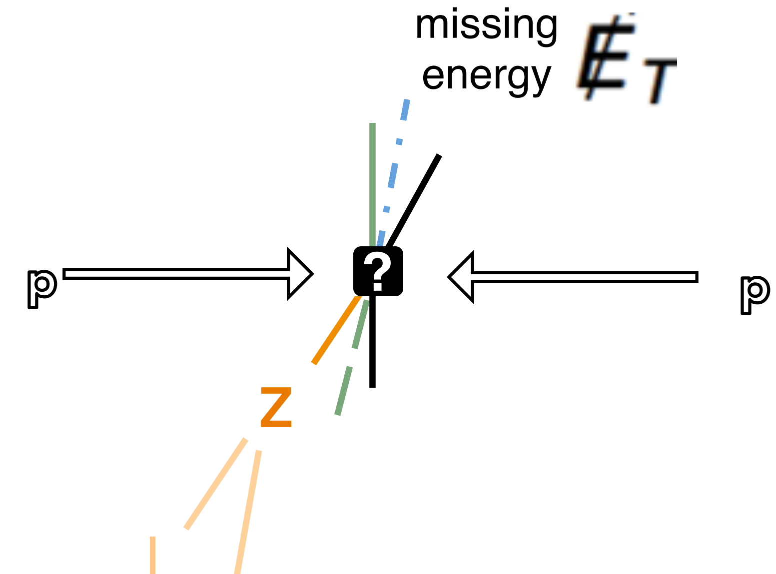
$$\rightarrow \left|\frac{f_a}{c_{\tilde{W}}}\right| > 2.38\ \text{TeV}$$

+ even more at LHC!

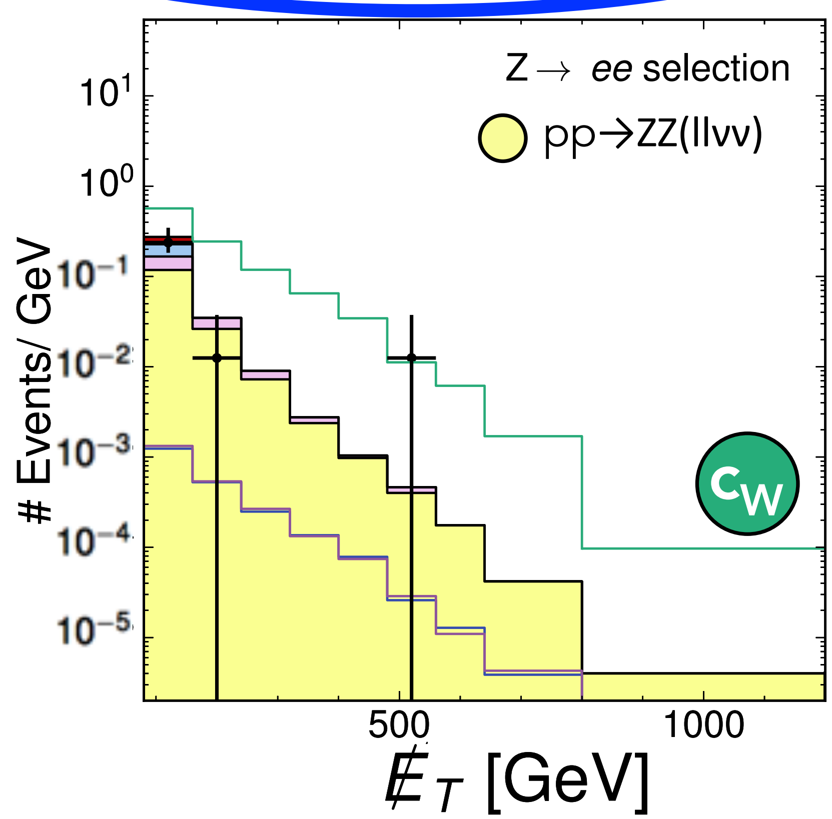
Mono - Z ALP signals

mono - Z:



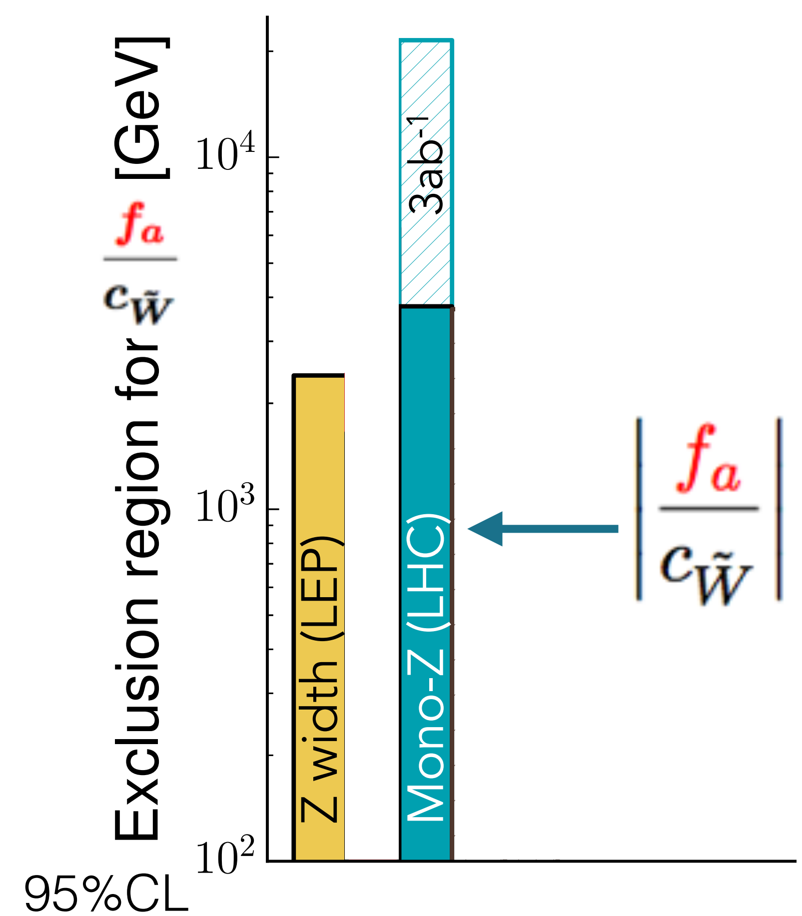


e.g. $$\mathbf{O}_{\tilde{W}} = -W^{a}_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a}$$



13 TeV 2.3 fb^{-1} CMS $Z + \not{E}_T$

$\not{E}_T > 80$ GeV $p_T^{\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $p_T^{\ell\ell} > 50$



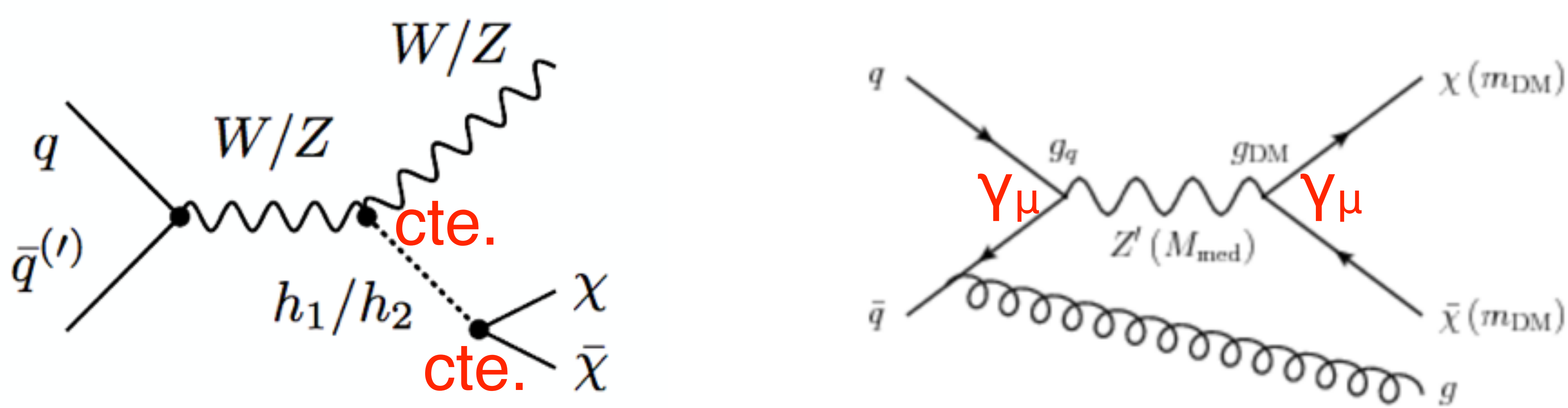
$$\left|\frac{f_a}{c_{\tilde{W}}}\right| > 3.77\ \text{TeV}$$

3ab^{-1}: assuming no improvement in systematics

A general, largely unexplored, ALP characteristic:
all couplings are derivative = grow with 4-momentum

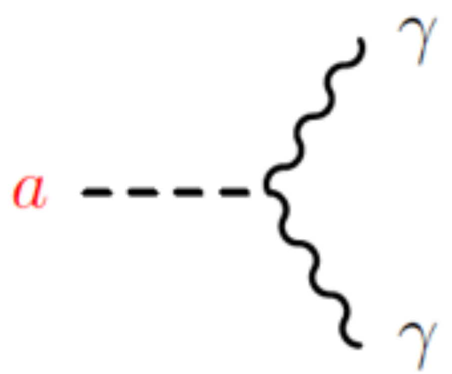
This is in contrast to SM and to most BSM searches:

for instance Z' or DM searches typically assume vectorial or scalar couplings:

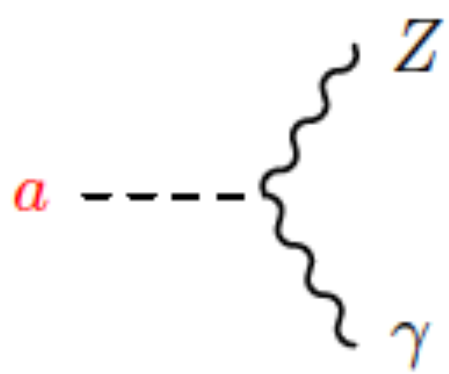


A general, largely unexplored, ALP characteristic:
all couplings are derivative = grow with 4-momentum

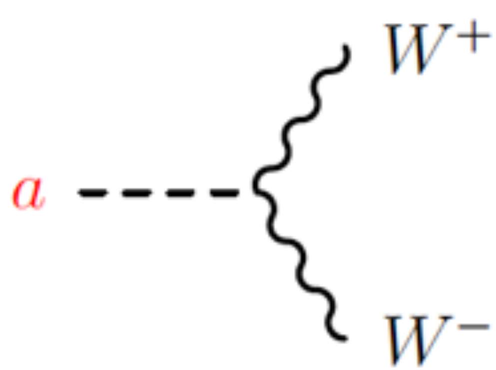
e.g.



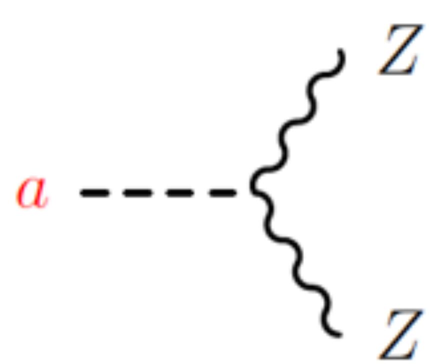
$$-\frac{4i}{f_a} p_{A1\alpha} p_{A2\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_\theta^2 c_{\tilde{B}} + s_\theta^2 c_{\tilde{W}}\right)$$



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

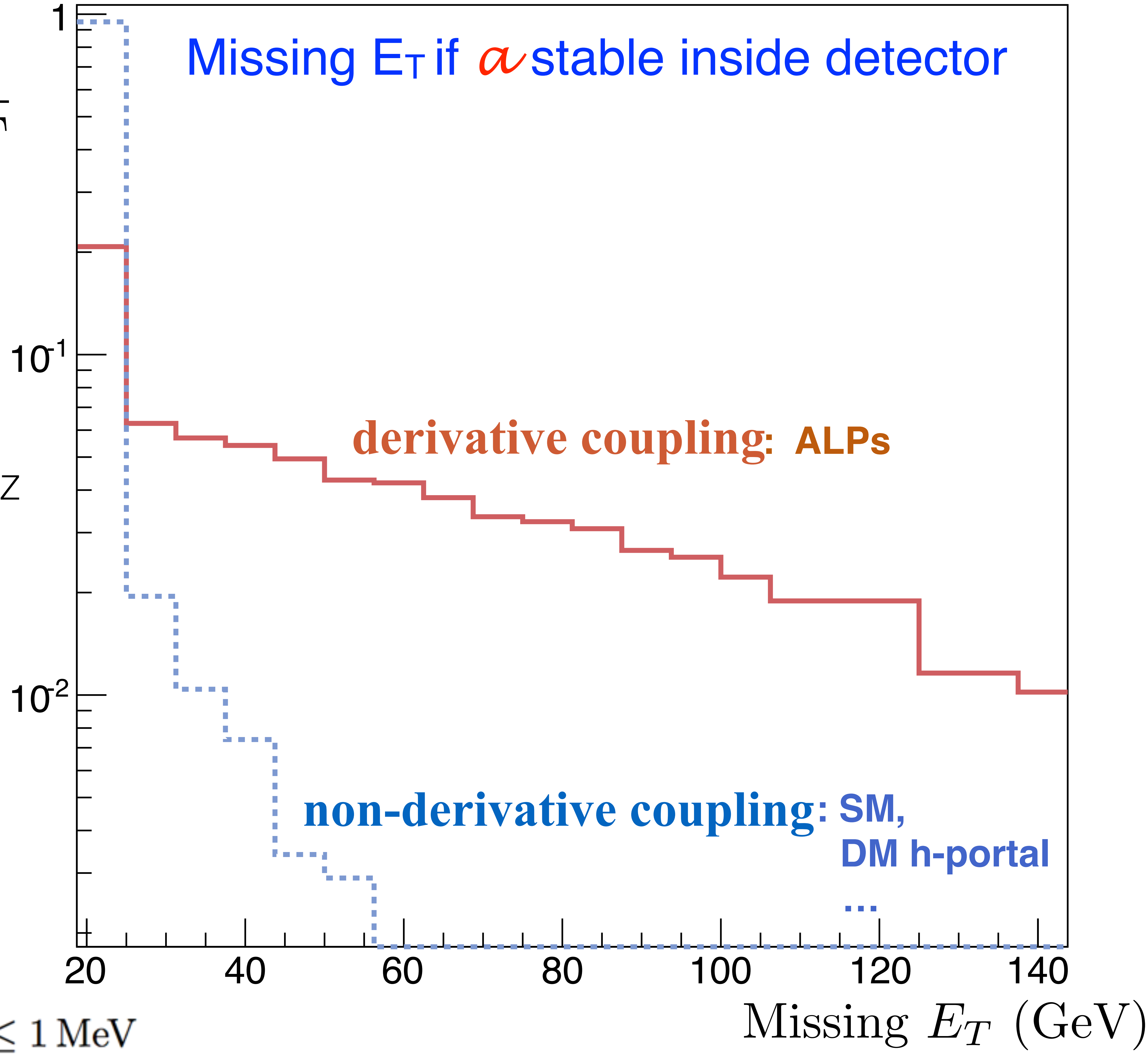


$$-\frac{4i}{f_a} c_{\tilde{W}} p_{+\alpha} p_{-\beta} \varepsilon^{\mu\nu\alpha\beta}$$



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

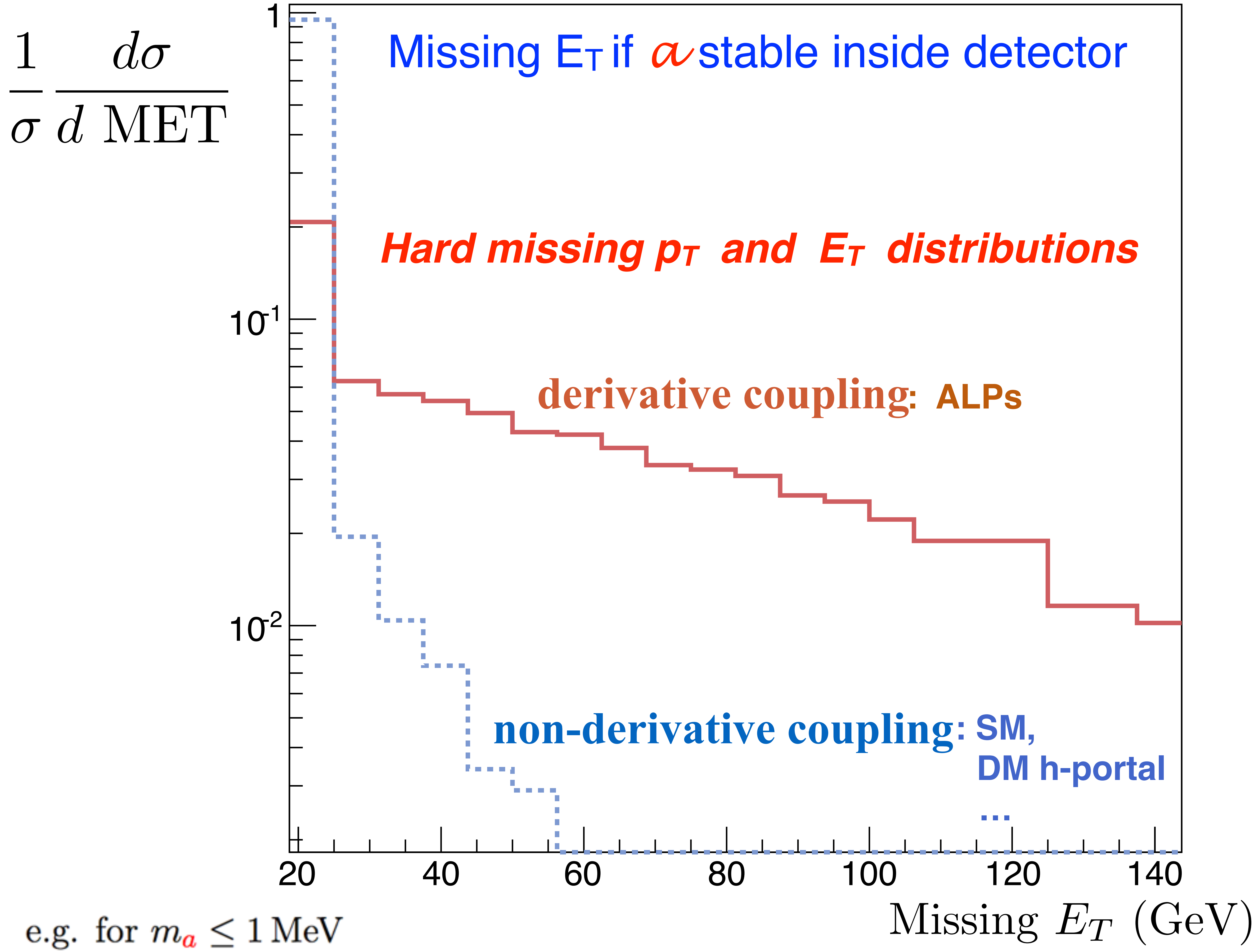
$$\frac{1}{\sigma}\frac{d\sigma}{d\,\mathrm{MET}}$$



example: mono-Z

SM: h-z-z con un h ligero
—> eta_munu

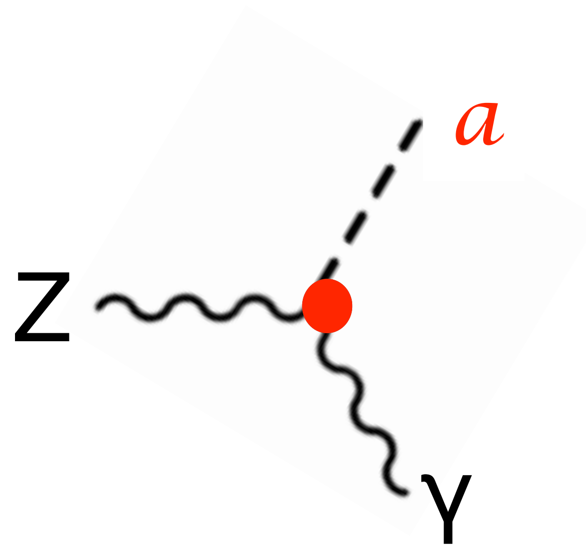
e.g. for $m_a \leq 1\,\mathrm{MeV}$



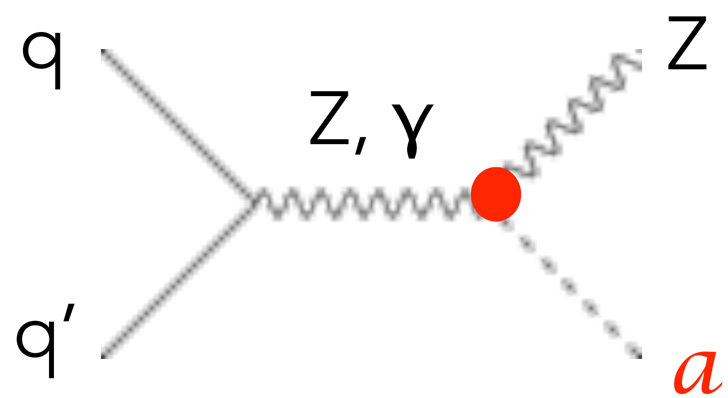
$\frac{1}{\sigma}\frac{d\sigma}{d\ \mathrm{MET}}$
Missing E_T if a stable inside detector
Hard missing p_T and E_T distributions
derivative coupling: ALPs
non-derivative coupling: SM, DM h-portal ...
1
10^{-1}
10^{-2}
20
40
60
80
100
120
140
Missing E_T (GeV)
e.g. for $m_a \leq 1\,\mathrm{MeV}$

We explored:

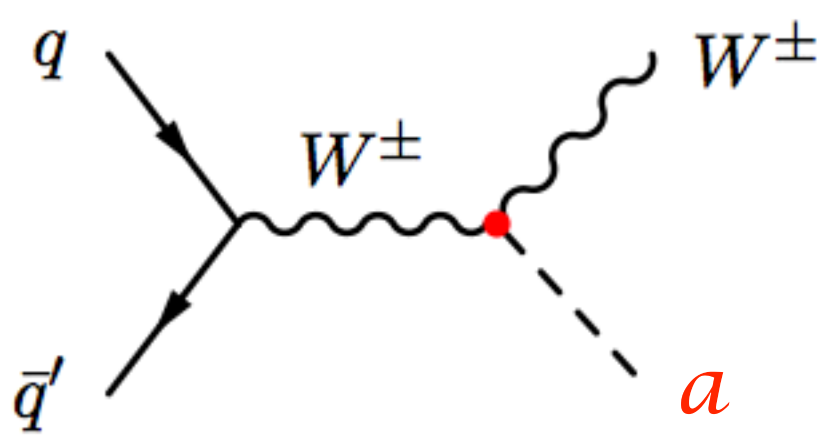
* LEP signals



* Mono-Z signals

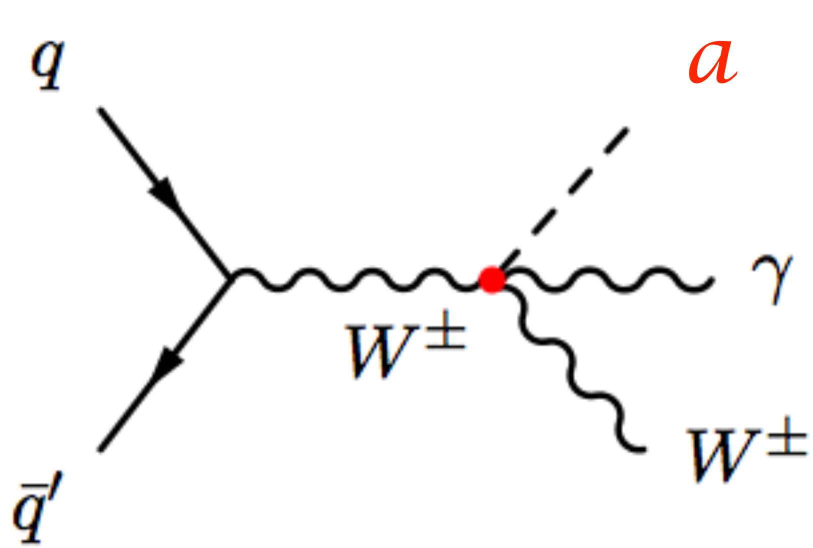


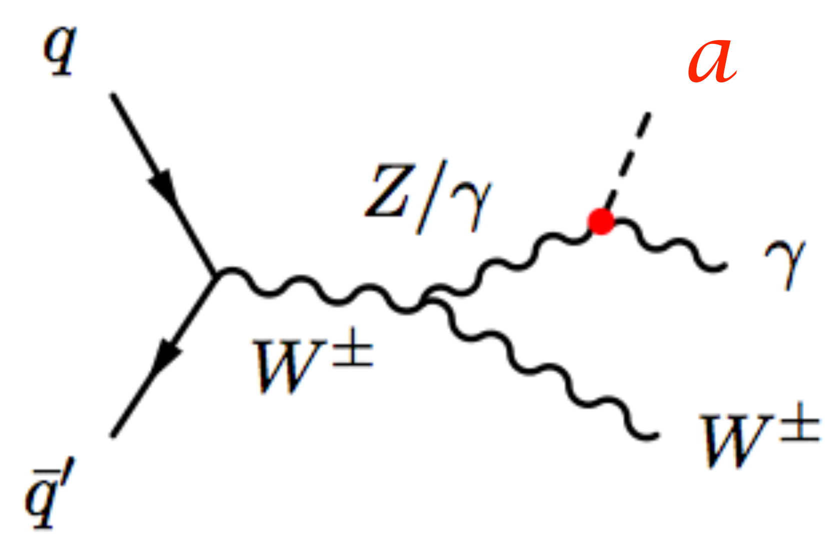
* Mono-W signals



for mono-Z/W we used present ATLAS and CMS searches and study prospects

* Associated ALP-γ-W

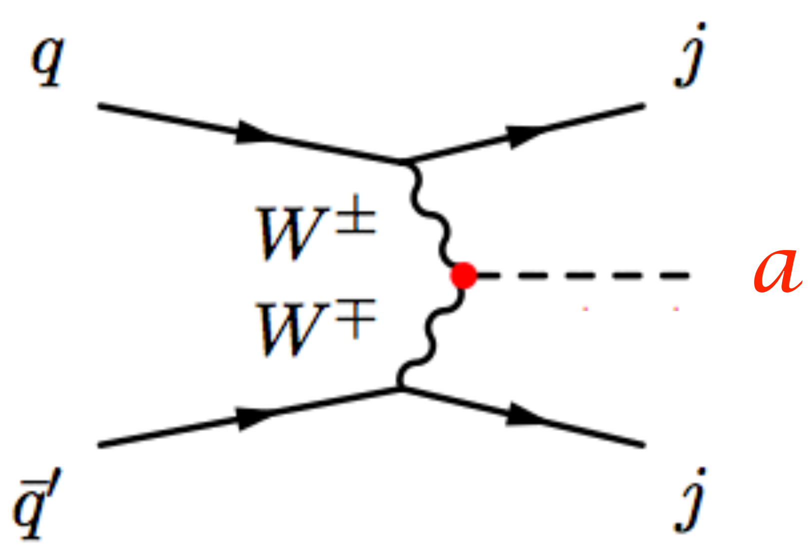


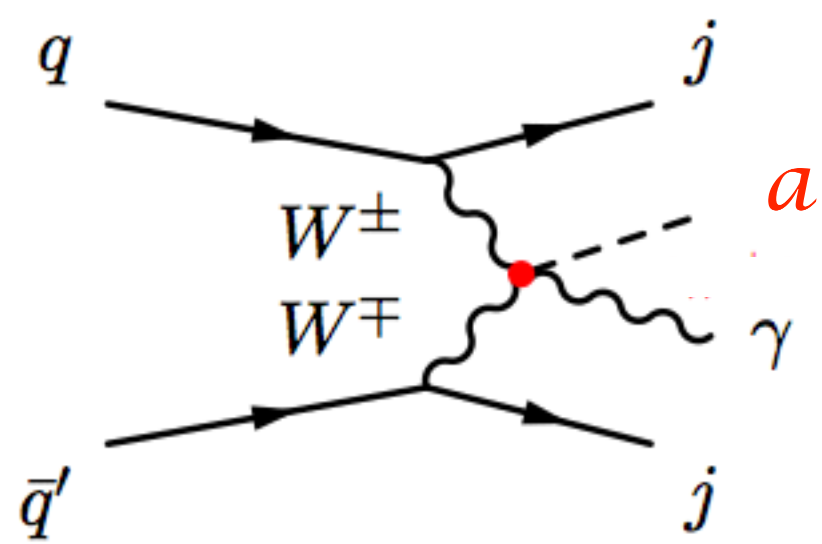


this channel not yet analysed by ATLAS and CMS

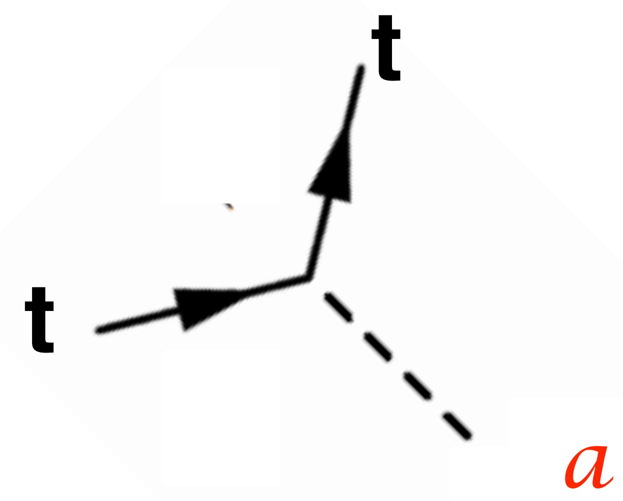
Promising at HL-LHC

* Others:





* ALP emission off a top as final state radiation at LHC:



We bound or showed a reach on $\frac{f_a}{c_i}$ within 0.5 - 16 TeV

for m_a < MeV or simply not decaying in the detector

	Observables/Processes		Linear
	Astrophysical obs.	$g_{a\gamma\gamma}$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\tilde{\mathbf{B}}}$
	Rare meson decays		$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\mathbf{a}\Phi}$
New constraints	**LEP data**		
	BSM Z width	$\Gamma(Z \to a\gamma)$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\tilde{\mathbf{B}}}$
	LHC processes		
	Non-standard h decays	$\Gamma(h \to aZ)$	
	Mono-Z prod.	$pp \to a\,Z$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\tilde{\mathbf{B}}}$ $c_{a\Phi}$
	Mono-W prod.	$pp \to a\,W^{\pm}$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $c_{\tilde{B}}$ $c_{a\Phi}$
Prospects	Associated prod.	$pp \to aW^{\pm}\gamma$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $c_{\tilde{B}}$ $c_{a\Phi}$
	VBF prod.	$pp \to ajj(\gamma)$	$c_{\tilde{W}}$ $c_{\tilde{B}}$ $c_{a\Phi}$
	Mono-h prod.	$pp \to h\,a$	
	$at\bar{t}$ prod.	$pp \to at\bar{t}$	$\mathbf{c}_{\mathbf{a}\Phi}$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a}$$

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

Higgs EFTs

Linear or **Chiral** (= non-linear)

||

SM EFT

Higgs EFTs

Linear or **Chiral**

II

SM EFT

Higgs field: $\Phi = (v+\mathbf{h})\ \mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

h is in an exact SU(2)$_L$ doublet

$\mathbf{U} = e^{i\pi^a\sigma^a/v}$

Longitudinal W,Z

Higgs EFTs

Linear or **Chiral** (non-linear)

in chiral: $$\Phi = \cancel{(v + \mathbf{h})}\ \mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

$\mathbf{U} = e^{i\pi^a\sigma^a/v}$

h may not be an <u>exact</u> $SU(2)_L$ doublet

Longitudinal W,Z

Higgs EFTs

Linear or **Chiral** (non-linear)

in chiral: $\Phi = (\cancel{v + \mathbf{h}})\ \mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

$\mathbf{U} = e^{i\pi^a\sigma^a/v}$

Longitudinal W,Z

Typical of "composite Higgs" models

e.g. in SO(5)/SO(4):

$$f\ \sin\left(\frac{\varphi}{2f}\right) = \frac{v}{2f}\cos\left(\frac{\mathbf{h}}{2f}\right) + \sqrt{1-\frac{v^2}{4f^2}}\sin\left(\frac{\mathbf{h}}{2f}\right) \neq (v+\mathbf{h})$$

Higgs EFTs

Linear or **Chiral** (non-linear)

in chiral: $\Phi = \cancel{(v+\mathbf{h})}\ \mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

$\mathbf{U} = e^{i\pi^a\sigma^a/v}$

Longitudinal W,Z

$$\mathcal{F}_i(\mathbf{h}) = 1 + a_i\mathbf{h}/v + b_i(\mathbf{h}/v)^2 + \ldots$$

Feruglio 93; Grinstein+Trott 07; Contino et al.10

Higgs EFTs

Linear or **Chiral** (non-linear)

in chiral: $\Phi = (v \cancel{+} \mathbf{h})\, \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$\mathbf{U} = e^{i\pi^a \sigma^a / v}$

Longitudinal W,Z

$$\mathcal{F}_i(\mathbf{h}) = 1 + a_i \mathbf{h}/v + b_i (\mathbf{h}/v)^2 + \ldots$$

Feruglio 93; Grinstein+Trott 07; Contino et al.10

independent !

some couplings decorrelate:
more operators at given order

the chiral expansion is an
expansion in derivatives

Higgs EFTs

Linear or **Chiral** (non-linear)

LO: $\mathscr{L}_a^{\mathrm{LO}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h)$ where $\mathcal{A}_{2D}(h) = iv^2 \frac{\partial^\mu a}{f_a} \mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\mathcal{F}_{2D}(h)$

with $\mathbf{V}_\mu(x) \equiv (\mathbf{D}_\mu \mathbf{U}(x))\,\mathbf{U}(x)^\dagger$

$\mathbf{T}(x) \equiv \mathbf{U}(x)\sigma_3\mathbf{U}(x)^\dagger$

Higgs EFTs

Linear or **Chiral** (non-linear)

LO: $\mathscr{L}_a^{\text{LO}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h)$ where $\mathcal{A}_{2D}(h) = iv^2 \frac{\partial^\mu a}{f_a}\text{Tr}[\mathbf{T}\mathbf{V}_\mu]\mathcal{F}_{2D}(h)$

$$ig\, Z_\mu\, \partial^\mu a \left(1 + 2a_{2D}\frac{\mathbf{h}}{v} + b_{2D}\frac{\mathbf{h}^2}{v^2}\right)$$

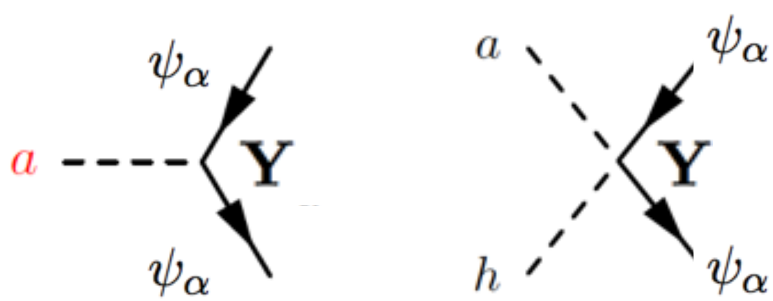
Higgs EFTs

Linear or **Chiral** (non-linear)

LO: $\mathscr{L}_a^{\rm LO} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h)$ where $\mathcal{A}_{2D}(h) = iv^2\,\frac{\partial^\mu a}{f_a}\,{\rm Tr}[\mathbf{T}\mathbf{V}_\mu]\,\mathcal{F}_{2D}(h)$

$$ig\,Z_\mu\,\partial^\mu a\left(1 + 2a_{2D}\frac{\mathbf{h}}{v} + b_{2D}\frac{\mathbf{h}^2}{v^2}\right)$$

$$\mathbf{U}(x) \to \mathbf{U}(x)\,e^{2i\,\mathbf{c_{2D}}\frac{a(x)}{f_a}}$$



as in the linear case

Higgs EFTs

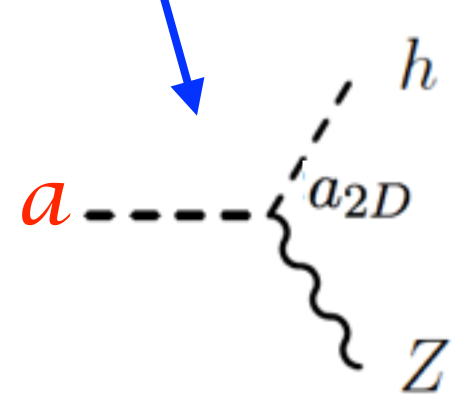
Linear or **Chiral** (non-linear)

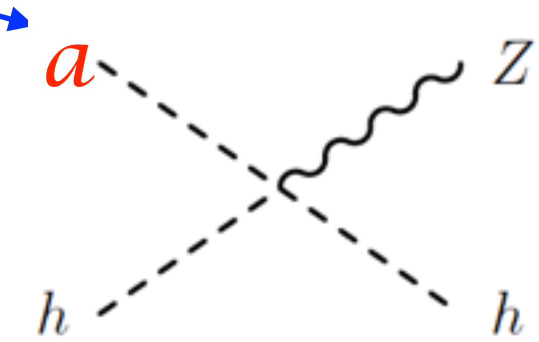
LO: $\mathscr{L}_a^{\rm LO} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h)$ where $\mathcal{A}_{2D}(h) = iv^2 \frac{\partial^\mu a}{f_a} \mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\mathcal{F}_{2D}(h)$

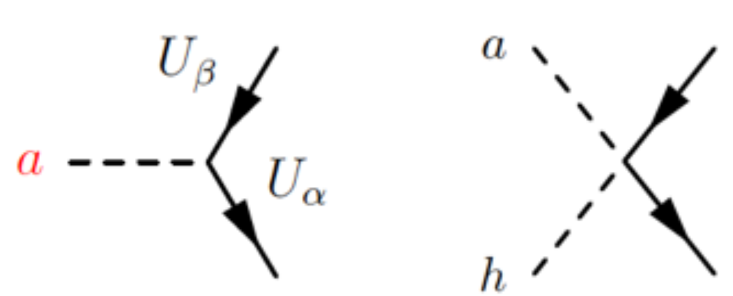
$$ig\, Z_\mu\, \partial^\mu a \left(1 + 2a_{2D}\frac{\mathbf{h}}{v} + b_{2D}\frac{\mathbf{h}^2}{v^2}\right)$$

ALP-Higgs couplings survive !!

(unlike linear case)







as in the linear case

Higgs EFTs

Linear or **Chiral** (non-linear)

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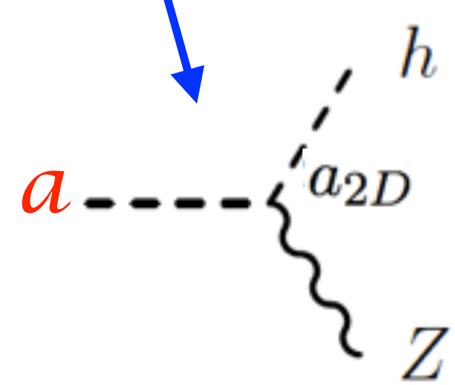
$$ig\, Z_\mu\, \partial^\mu a \left(1 + 2a_{2D}\frac{\mathbf{h}}{v} + b_{2D}\frac{\mathbf{h}^2}{v^2}\right)$$

ALP-Higgs couplings survive !!

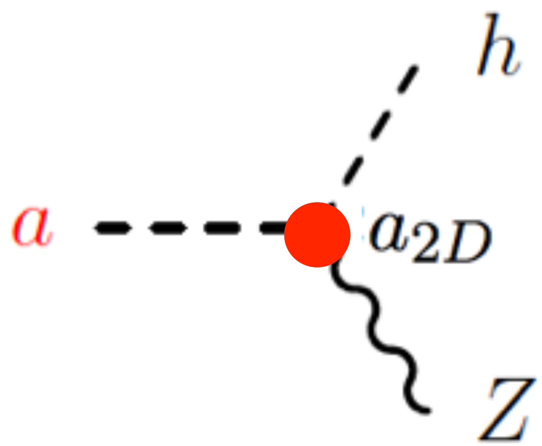
(unlike linear case: at NNLO)



New additional signals: mono-h, BSM Higgs decays

(we also proposed first this type of ALP signals)

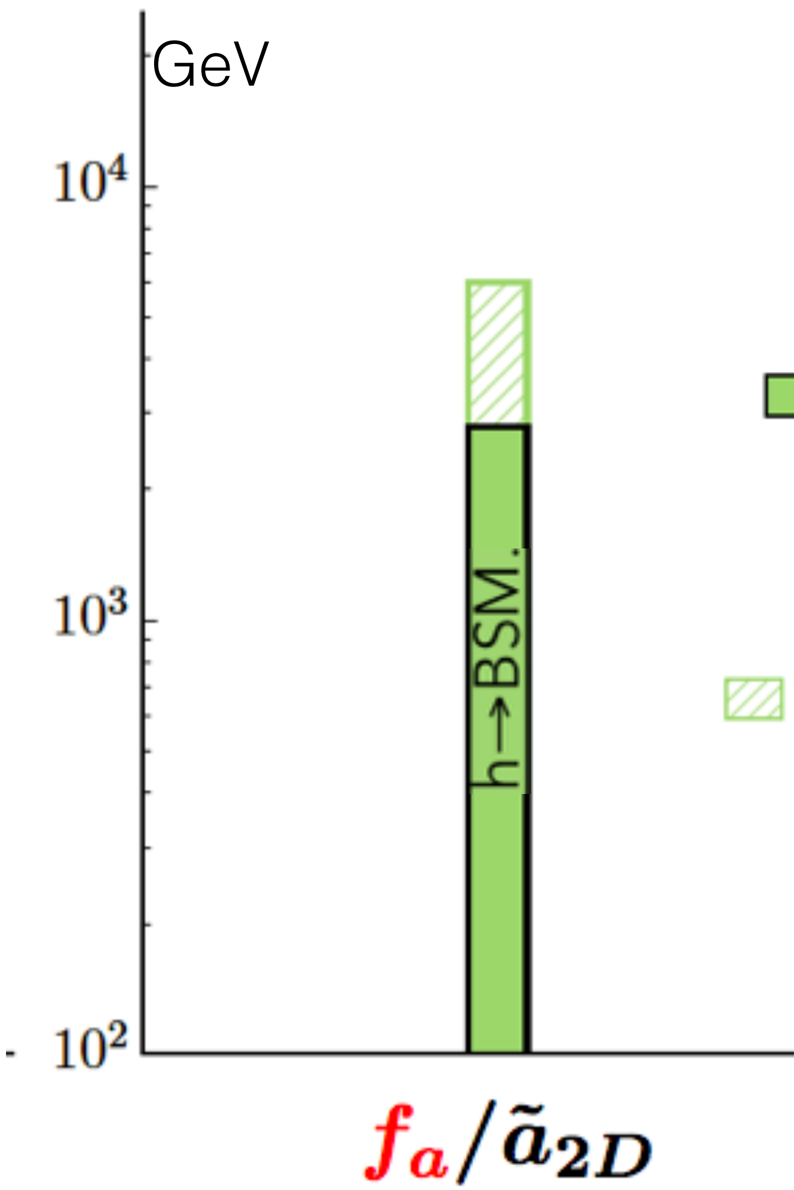
Non-standard Higgs decays



$$\Gamma_{\rm BSM} \;=\; \Gamma_{\mathbf{h}\to\mathbf{a}Z} + \Gamma_{\mathbf{h}\to\mathbf{a}Z\gamma} + \Gamma_{\mathbf{h}\to\mathbf{a}\,\mathrm{f\bar{f}}}$$

$$\mathrm{Br}(h \to \mathrm{BSM}) = \frac{\Gamma_{\rm BSM}}{\Gamma_{\rm BSM} + \Gamma_{\rm SM}} \lesssim 0.34 \qquad (95\%\ \mathrm{C.L.})$$

ATLAS and CMS
7 and 8 TeV

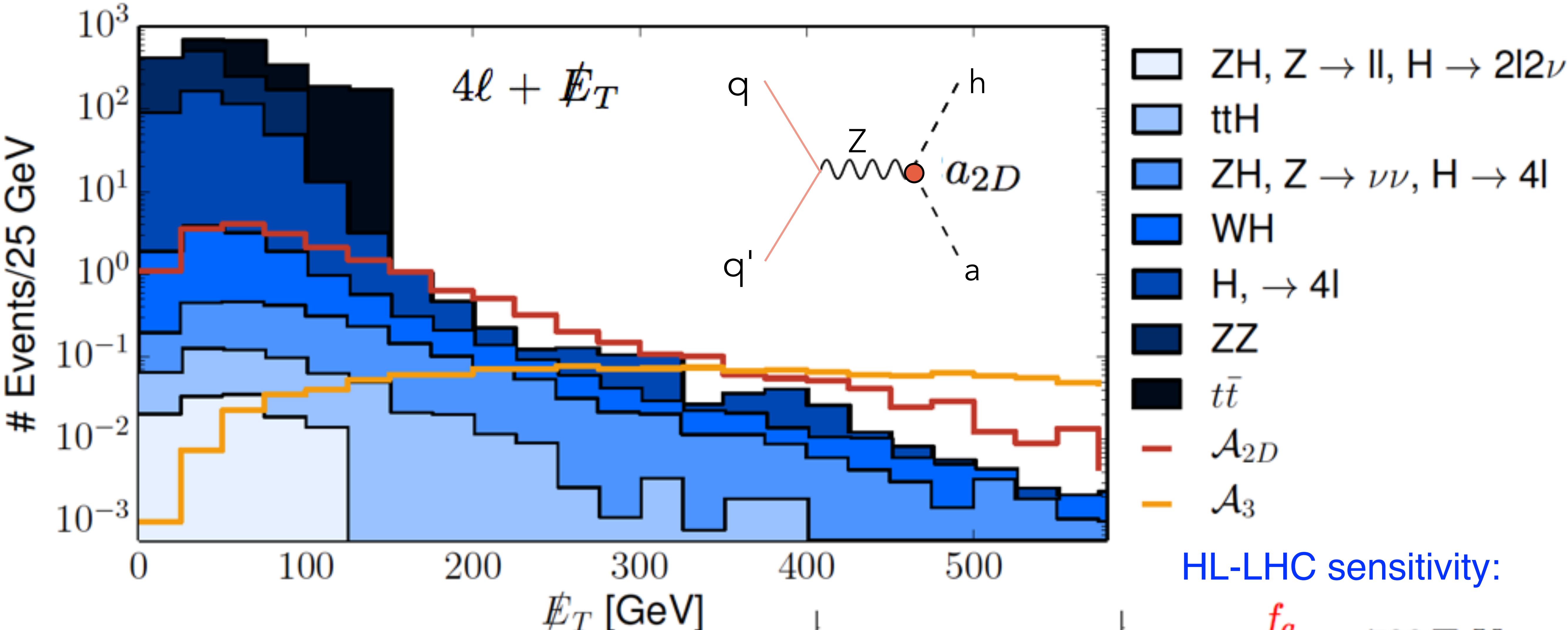


BR($h \to$ BSM) $\qquad \dfrac{f_a}{\tilde{a}_{2D}} \gtrsim 2.78\ \mathrm{TeV}$

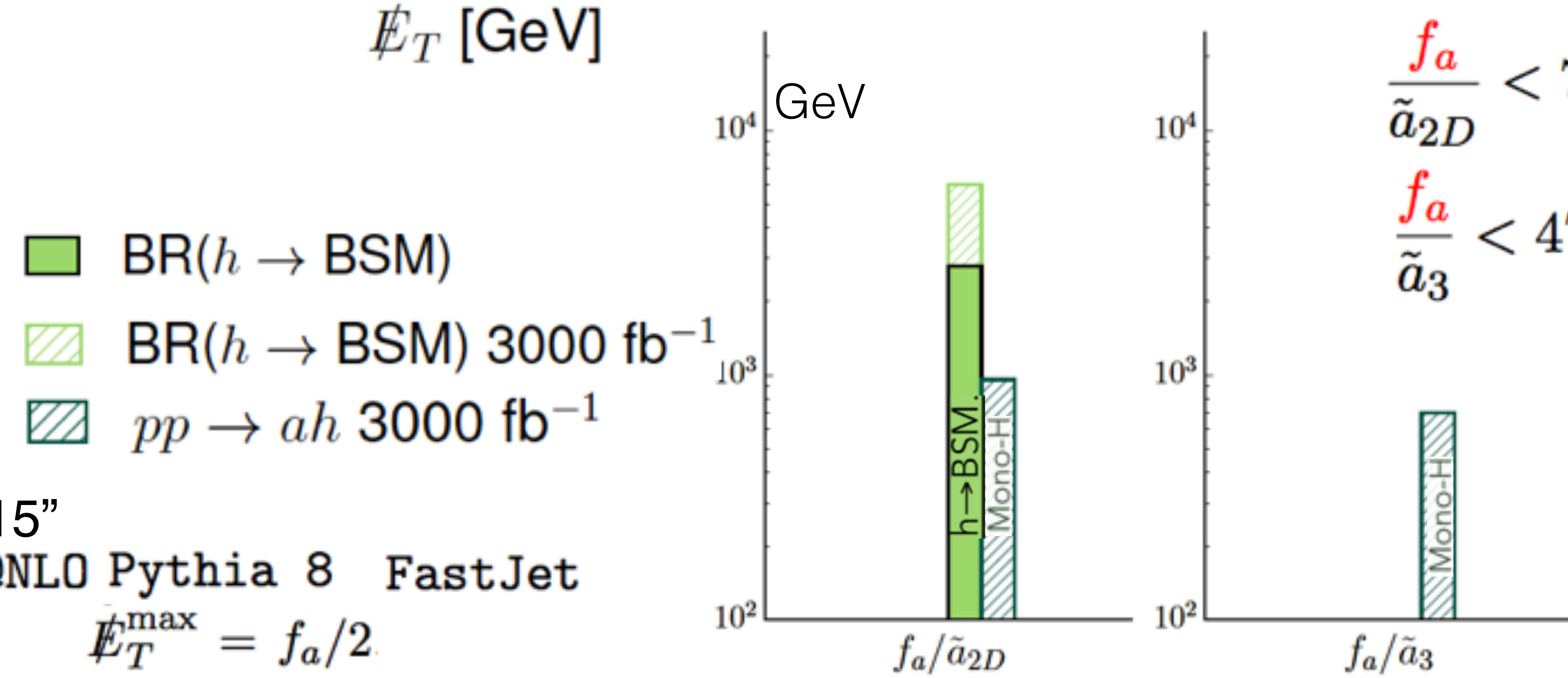
BR($h \to$ BSM) 3000 fb^{-1} $\qquad \dfrac{f_a}{\tilde{a}_{2D}} \gtrsim 6\ \mathrm{TeV}$

for $\quad m_a \lesssim 34\ \mathrm{GeV}$

Mono-Higgs : pp —> *a* h



HL-LHC sensitivity:



$$\frac{f_a}{\tilde{a}_{2D}} < 780\ \mathrm{TeV}$$

$$\frac{f_a}{\tilde{a}_3} < 470\ \mathrm{TeV}$$

"Les Houches 2015"

MadGraph5_aMC@NLO Pythia 8 FastJet

$\not\!\!E_T^{\rm min} = 150\,\mathrm{GeV}$ $\quad \not\!\!E_T^{\rm max} = f_a/2$

Higgs EFTs

Linear or **Chiral** (non-linear)

LO: $\mathscr{L}_a^{\rm LO} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h)$ where $\mathcal{A}_{2D}(h) = iv^2 \frac{\partial^\mu a}{f_a} \mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\mathcal{F}_{2D}(h)$

NLO, bosonic custodial preserving:

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

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

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

$$\mathcal{A}_1(h) = \frac{i}{4\pi}\tilde{B}_{\mu\nu}\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_1(h)$$

$$\mathcal{A}_2(h) = \frac{i}{4\pi}\mathrm{Tr}[\tilde{W}_{\mu\nu}\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_2(h)$$

$$\mathcal{A}_3(h) = \frac{1}{4\pi}B_{\mu\nu}\frac{\partial^\mu a}{f_a}\partial^\nu\,\mathcal{F}_3(h)$$

$$\mathbf{V}_\mu(x) \equiv (\mathbf{D}_\mu \mathbf{U}(x))\,\mathbf{U}(x)^\dagger$$

NLO bosonic, custodial breaking:

$$\mathcal{A}_4(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}_\nu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_4(h)$$

$$\mathcal{A}_5(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\nu]\frac{\partial_\nu a}{f_a}\,\mathcal{F}_5(h)$$

$$\mathcal{A}_6(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}[W_{\mu\nu},\mathbf{V}^\mu]]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_6(h)$$

$$\mathcal{A}_7(h) = \frac{i}{4\pi}\mathrm{Tr}[\mathbf{T}\tilde{W}_{\mu\nu}]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_7(h)$$

$$\mathcal{A}_8(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[[\mathbf{V}_\nu,\mathbf{T}]\mathcal{D}_\mu\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_8(h)$$

$$\mathcal{A}_9(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}_\nu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_9(h)$$

$$\mathcal{A}_{10}(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}W_{\mu\nu}]\frac{\partial^\mu a}{f_a}\partial^\nu\,\mathcal{F}_{10}(h)$$

$$\mathcal{A}_{11}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\Box a}{f_a}\partial^\mu\,\mathcal{F}_{11}(h)$$

$$\mathcal{A}_{12}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu\partial^\nu a}{f_a}\partial_\nu\,\mathcal{F}_{12}(h)$$

$$\mathcal{A}_{13}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu a}{f_a}\Box\,\mathcal{F}_{13}(h)$$

$$\mathcal{A}_{14}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial_\nu a}{f_a}\partial^\mu\partial^\nu\mathcal{F}_{14}(h)$$

$$\mathcal{A}_{15}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu a}{f_a}\partial_\nu\,\mathcal{F}_{15}(h)\partial^\nu\,\mathcal{F}'_{15}(h)$$

$$\mathcal{A}_{16}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial_\nu a}{f_a}\partial^\mu\,\mathcal{F}_{16}(h)\partial^\nu\,\mathcal{F}'_{16}(h)$$

$$\mathcal{A}_{17}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu\Box a}{f_a}\,\mathcal{F}_{17}(h)\,.$$

We also determined the complete basis of non-redundant bosonic +fermionic couplings at NLO

NLO bosonic, custodial breaking:

$$\mathcal{A}_4(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}_\nu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_4(h)$$

$$\mathcal{A}_5(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\nu]\frac{\partial_\nu a}{f_a}\,\mathcal{F}_5(h)$$

$$\mathcal{A}_6(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}[W_{\mu\nu},\mathbf{V}^\mu]]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_6(h)$$

$$\mathcal{A}_7(h) = \frac{i}{4\pi}\mathrm{Tr}[\mathbf{T}\tilde{W}_{\mu\nu}]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_7(h)$$

$$\mathcal{A}_8(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[[\mathbf{V}_\nu,\mathbf{T}]\mathcal{D}_\mu\mathbf{V}^\mu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_8(h)$$

$$\mathcal{A}_9(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}_\nu]\frac{\partial^\nu a}{f_a}\,\mathcal{F}_9(h)$$

$$\mathcal{A}_{10}(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}W_{\mu\nu}]\frac{\partial^\mu a}{f_a}\partial^\nu\,\mathcal{F}_{10}(h)$$

$$\mathcal{A}_{11}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\Box a}{f_a}\partial^\mu\,\mathcal{F}_{11}(h)$$

$$\mathcal{A}_{12}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu\partial^\nu a}{f_a}\partial_\nu\,\mathcal{F}_{12}(h)$$

$$\mathcal{A}_{13}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu a}{f_a}\Box\,\mathcal{F}_{13}(h)$$

$$\mathcal{A}_{14}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial_\nu a}{f_a}\partial^\mu\partial^\nu\mathcal{F}_{14}(h)$$

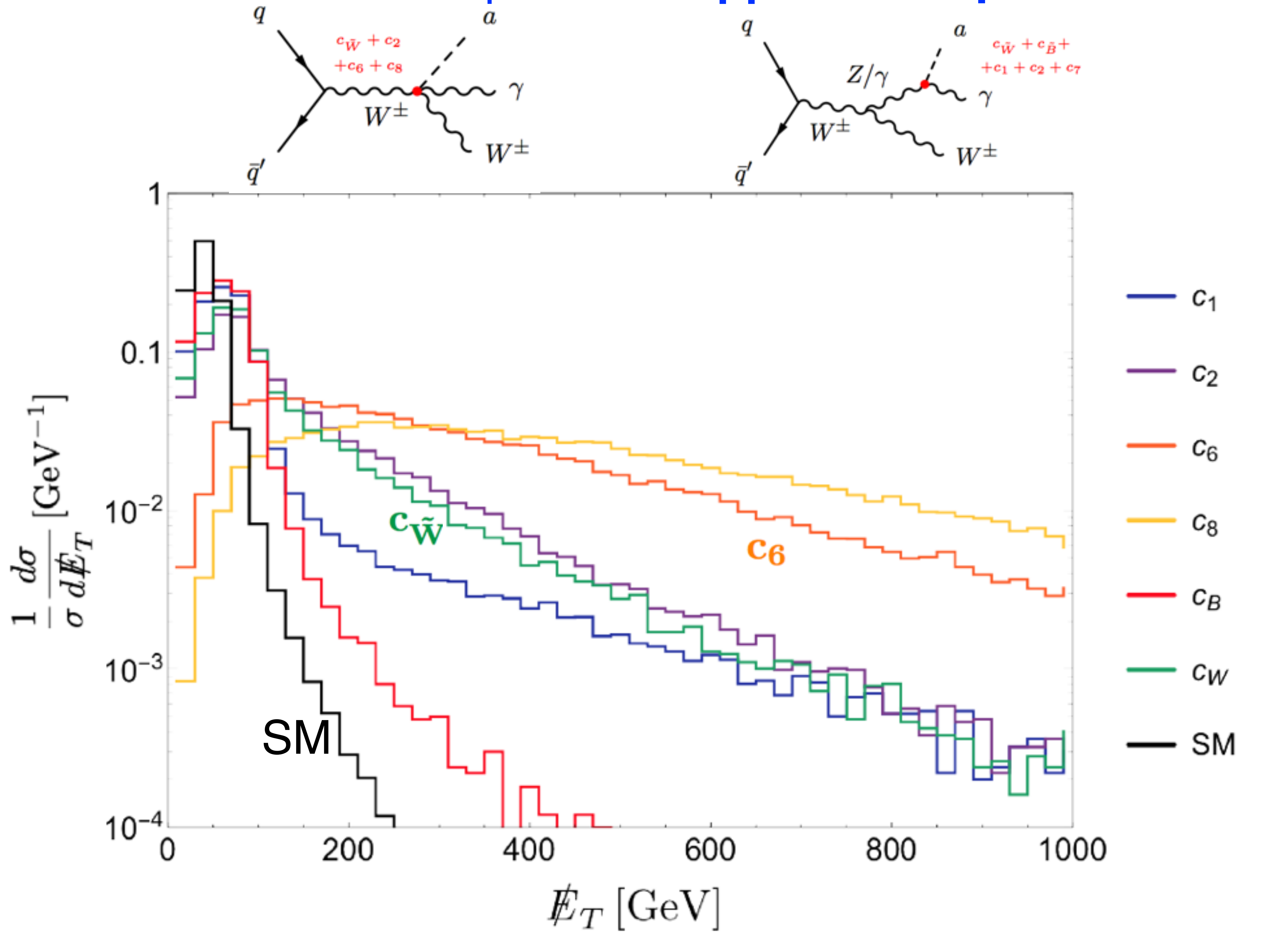
$$\mathcal{A}_{15}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu a}{f_a}\partial_\nu\,\mathcal{F}_{15}(h)\partial^\nu\,\mathcal{F}'_{15}(h)$$

$$\mathcal{A}_{16}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial_\nu a}{f_a}\partial^\mu\,\mathcal{F}_{16}(h)\partial^\nu\,\mathcal{F}'_{16}(h)$$

$$\mathcal{A}_{17}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\frac{\partial^\mu\Box a}{f_a}\,\mathcal{F}_{17}(h)\,.$$

We also determined the complete basis of non-redundant bosonic +fermionic couplings at NLO

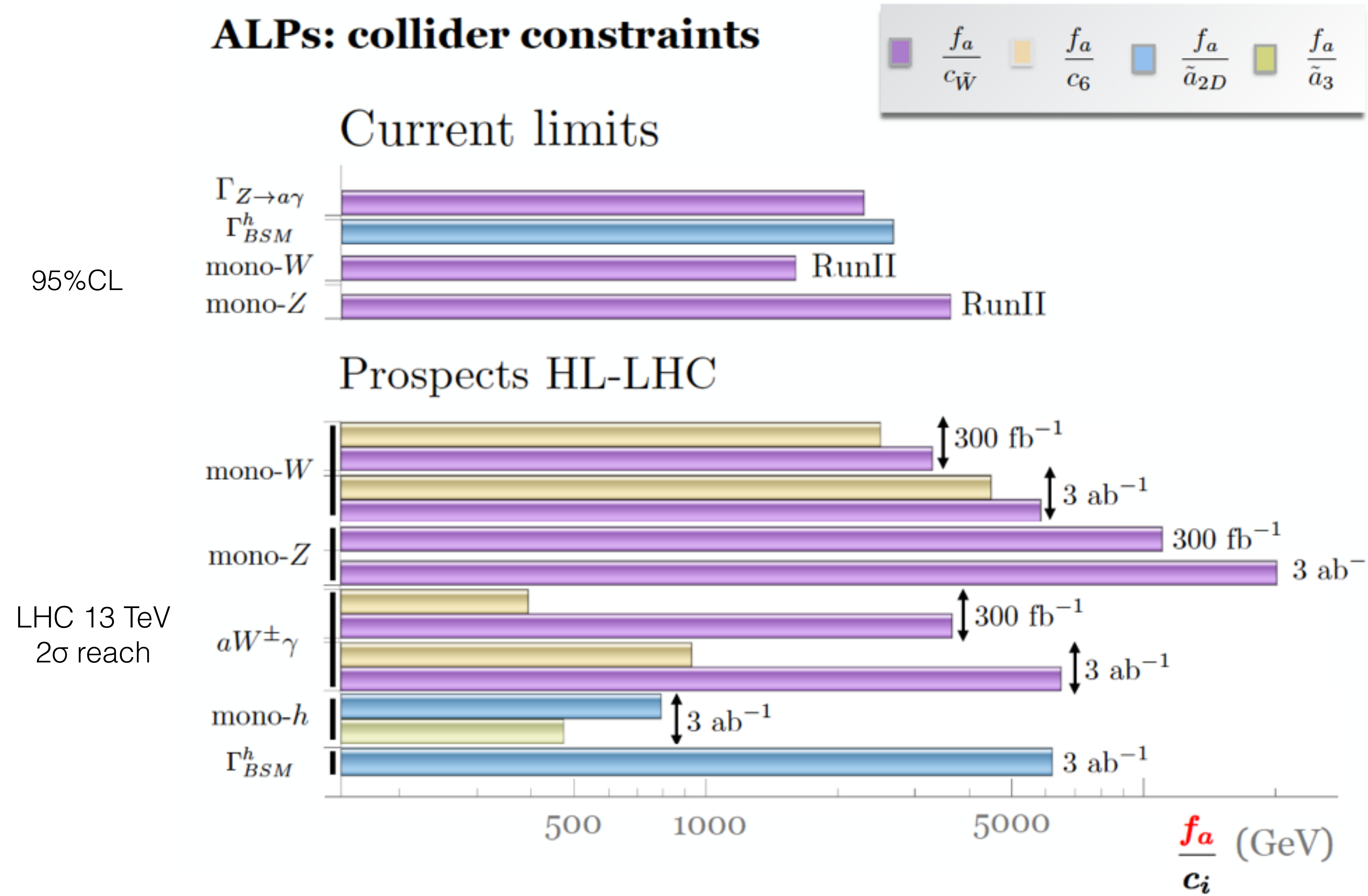
Associated production **pp —>** a**Wγ**



	Observables/Processes		**Linear**
	Astrophysical obs.	$g_{a\gamma\gamma}$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\tilde{\mathbf{B}}}$
	Rare meson decays		$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\mathbf{a}\Phi}$
New constraints	**LEP data**		
	BSM Z width	$\Gamma(Z \to a\gamma)$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\tilde{\mathbf{B}}}$
	LHC processes		
	Non-standard h decays	$\Gamma(h \to aZ)$	
	Mono-Z prod.	$pp \to a\,Z$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $\mathbf{c}_{\tilde{\mathbf{B}}}$ $c_{a\Phi}$
	Mono-W prod.	$pp \to a\,W^{\pm}$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $c_{\tilde{B}}$ $c_{a\Phi}$
Prospects	Associated prod.	$pp \to aW^{\pm}\gamma$	$\mathbf{c}_{\tilde{\mathbf{W}}}$ $c_{\tilde{B}}$ $c_{a\Phi}$
	VBF prod.	$pp \to ajj(\gamma)$	$c_{\tilde{W}}$ $c_{\tilde{B}}$ $c_{a\Phi}$
	Mono-h prod.	$pp \to h\,a$	
	$at\bar{t}$ prod.	$pp \to at\bar{t}$	$\mathbf{c}_{\mathbf{a}\Phi}$

	Observables/Processes		Parameters contributing: Linear	Parameters contributing: 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**			
New constraints	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
New constraints	**LHC processes**			
New constraints	Non-standard h decays	$\Gamma(h \to aZ)$		$\mathbf{\tilde{a}_{2D}}$ $\tilde{a}_3$ $\tilde{a}_{10}$ $\tilde{a}_{11-14}$ $\tilde{a}_{17}$
New constraints	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}
New constraints	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
Prospects	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
Prospects	Mono-h prod.	$pp \to h\,a$		$\mathbf{\tilde{a}_{2D}}$ $\mathbf{\tilde{a}_3}$ $\mathbf{\tilde{a}_{10}}$ $\tilde{a}_{11-14}$ $\tilde{a}_{17}$
Prospects	$at\bar{t}$ prod.	$pp \to at\bar{t}$	$\mathbf{c_{a\Phi}}$	$\mathbf{c_{2D}}$

ALPs: collider constraints



flattish MET are ALP signals

Conclusions

* (pseudo) Goldstone Bosons in **solutions to fundamental SM problems** and BSM theories —> derivative couplings.

Strong case for hunting them

* **New theoretical development: ALP effective Lagrangian for non-linear EWSB. —> ALP-Higgs-V signals!**

* **New ALP signals from linear(SMEFT) and non-linear Lags.**

MET (if a decaying beyond detector) —> mono-γ, -W/Z, -h, $\Gamma_{BSM}(h)$

besides rare decays

Fish for them in your data!

To do: a decaying inside detector

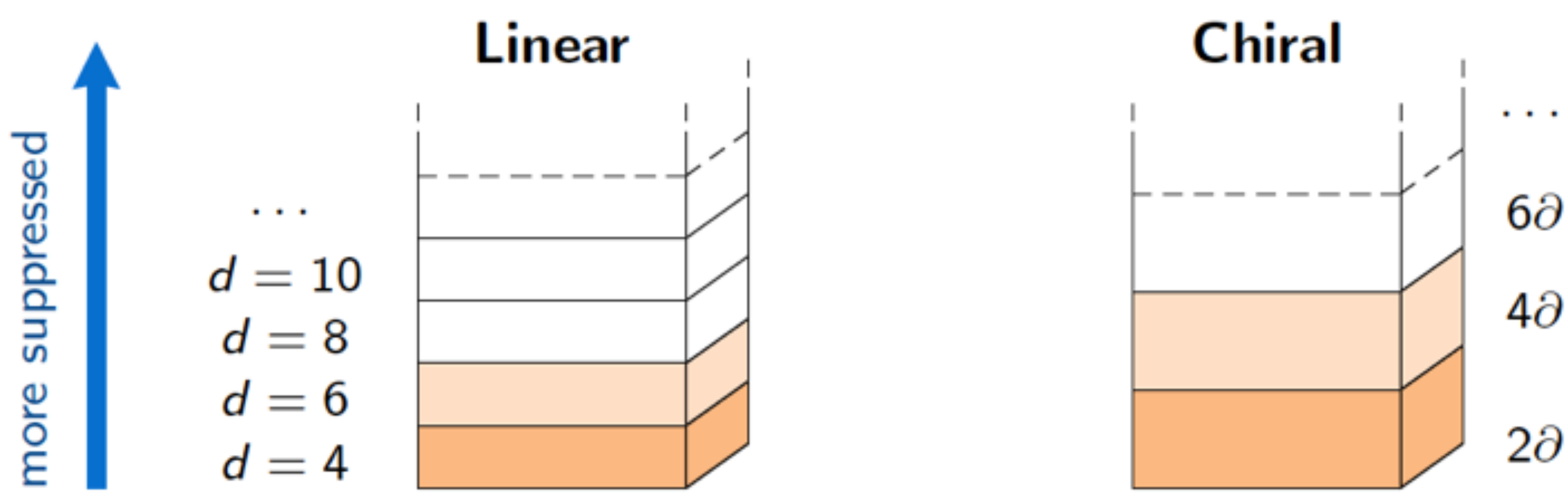
Backup

Higgs EFTs

Linear (SMEFT) versus **Chiral** (non-linear)

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.

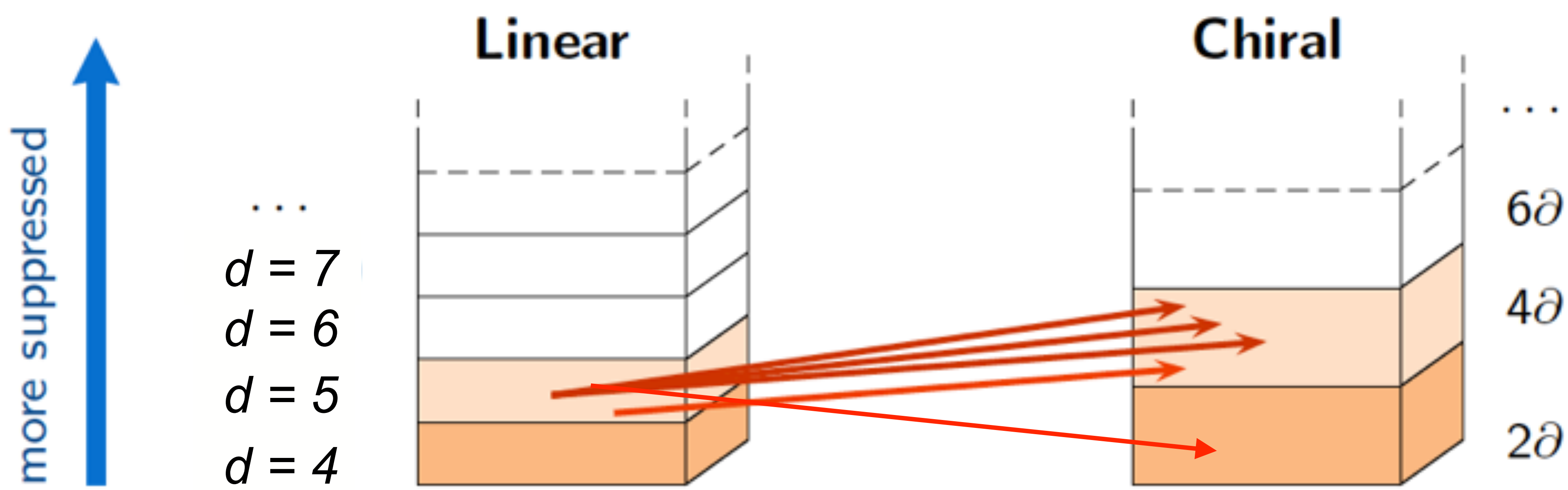


Higgs EFTs

Linear (SMEFT) versus **Chiral** (non-linear)

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.



correlations:
$D_\mu \Phi \sim (v+h) D_\mu \mathbf{U} + \partial_\mu h \mathbf{U}$

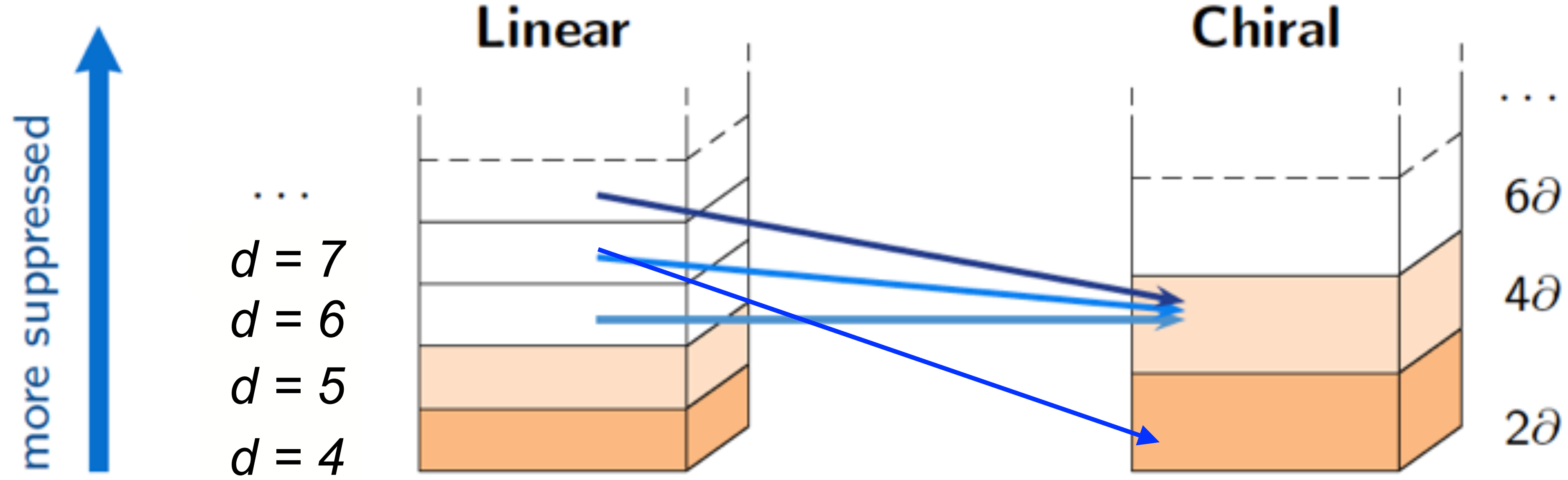
decorrelations:
$D_\mu \mathbf{U}$ and $\partial_\mu h$ independent

Higgs EFTs

Linear (SMEFT) versus **Chiral** (non-linear)

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.



Connected to NLO $d=5$ operators in the linear expansion

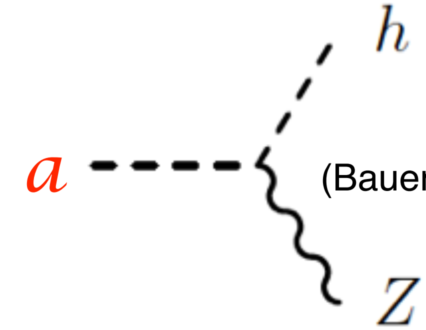
LO Chiral: Fermionic vertices induced by $\mathcal{A}_{2D} \longrightarrow \quad \frac{-i}{2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)\frac{\partial_\mu a}{f_a}$

NLO Chiral

$$\left\{\begin{array}{lcl}\mathcal{A}_{\tilde{B}} & \longrightarrow & -B_{\mu\nu}\tilde{B}^{\mu\nu}\dfrac{a}{f_a} \\ \mathcal{A}_{\tilde{W}} & \longrightarrow & -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\dfrac{a}{f_a} \\ \mathcal{A}_{\tilde{G}} & \longrightarrow & -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\dfrac{a}{f_a}\end{array}\right.$$

Connected to NNLO $d=7$ operators in the linear

LO Chiral: Bosonic vertices induced by $\mathcal{A}_{2D}$ $\longrightarrow$



(Bauer, Neubert, Tham 2016)

NLO Chiral

$$\mathcal{A}_1 \longrightarrow -\frac{2i}{(4\pi)v^2}\tilde{B}_{\mu\nu}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\frac{\partial_\nu a}{f_a}$$

$$\mathcal{A}_2 \longrightarrow -\frac{i}{(4\pi)v^2}(D_\mu\Phi^\dagger \tilde{W}^{\mu\nu}\Phi - \Phi^\dagger \tilde{W}^{\mu\nu} D_\mu\Phi)\frac{\partial^\nu a}{f_a}$$

$$\mathcal{A}_3 \longrightarrow \frac{-2}{(4\pi)v^2}B_{\mu\nu}\frac{\partial^\mu a}{f_a}D(\Phi^\dagger\Phi)$$

$$\mathcal{A}_4,\, \mathcal{A}_8 \longrightarrow \frac{4i}{(4\pi)^2v^2}(D^\mu\Phi^\dagger D_\mu D_\nu\Phi - D_\mu D_\nu\Phi^\dagger D^\mu\Phi)\frac{\partial^\nu a}{f_a}$$

$$\mathcal{A}_5 \longrightarrow \frac{4i}{(4\pi)^2v^2}(D^\nu\Phi^\dagger\Box\Phi - \Box\Phi^\dagger D^\mu\Phi)\frac{\partial_\nu a}{f_a}$$

$$\mathcal{A}_6 \longrightarrow -\frac{4}{(4\pi)iv^2}(\Phi^\dagger W_{\mu\nu}D^\mu\Phi + D^\mu\Phi^\dagger W_{\mu\nu}\Phi)\frac{\partial^\nu a}{f_a}$$

$$\mathcal{A}_{10} \longrightarrow \frac{4}{(4\pi)v^2}(\Phi^\dagger W_{\mu\nu}D^\mu\Phi + D^\mu\Phi^\dagger W_{\mu\nu}\Phi)\frac{\partial^\nu a}{f_a}$$

$$\mathcal{A}_{11} \longrightarrow -\frac{2i}{(4\pi)^2v^2}(\Phi^\dagger\Box\Phi - \Phi\Box\Phi^\dagger)\frac{\Box a}{f_a}$$

$$\mathcal{A}_{12} \longrightarrow -\frac{2i}{(4\pi)^2v^2}(\Phi^\dagger \overleftrightarrow{D_\mu D_\nu}\Phi)\frac{\partial^\mu\partial^\nu a}{f_a}$$

$$\mathcal{A}_{15},\, \mathcal{A}_{16} \longrightarrow -\frac{8i}{(4\pi)^2v^2}(D^\mu\Phi^\dagger D_\mu D_\nu\Phi - D_\mu D_\nu\Phi^\dagger D^\mu\Phi)\frac{\partial^\nu a}{f_a}$$

$$\mathcal{A}_{17} \longrightarrow 2\frac{2i}{(4\pi)^2v^2}(\Phi^\dagger D_\mu\Phi)\frac{\partial^\mu\Box a}{f_a}$$

Connected to N^{3}LO $d = 9$ operators in the linear expansion

NLO Chiral

$$\left\{\begin{aligned} \mathcal{A}_7 &\longrightarrow \frac{8i}{(4\pi)^2 v^4}(\Phi^\dagger \tilde{W}_{\mu\nu}\Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)\frac{\partial^\nu a}{f_a} \\ \mathcal{A}_{13} &\longrightarrow -\frac{4i}{(4\pi)^2 v^4}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\Box[\Phi^\dagger\Phi]\frac{\partial^\mu a}{f_a} \\ \mathcal{A}_{14} &\longrightarrow -\frac{4i}{(4\pi)^2 v^4}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\partial^\mu\partial^\nu[\Phi^\dagger\Phi]\frac{\partial_\nu a}{f_a} \end{aligned}\right.$$

Connected to N^{4}LO $d = 11$ operators in the linear expansion

NLO Chiral: $\mathcal{A}_9 \longrightarrow -\frac{i}{2\pi v^6}(\Phi^\dagger D_\mu \Phi)(\Phi^\dagger D^\mu \Phi)(\Phi^\dagger D_\nu \Phi)\frac{\partial^\nu a}{f_a}$

Validity of the EFT

f_a must be significantly larger than the typical energies of the process.

For each given f_a, validity conditions:

- $\boxed{m_T^{\max} < f_a}$ for mono-Ws, because the ATLAS search uses m_T as discriminating variable; $m_T^{\max}$ denotes the highest m_T data bin.
- $\boxed{2\not{E}_T^{\max} < f_a}$ for the rest of accelerator signals, where $\not{E}_T^{\max}$ denotes the highest $\not{E}_T$ data bin.

e.g. In mono-Z analysis with 2.3 fb^{-1}, the $\not{E}_T$ value for the highest bin considered is 1.2 TeV

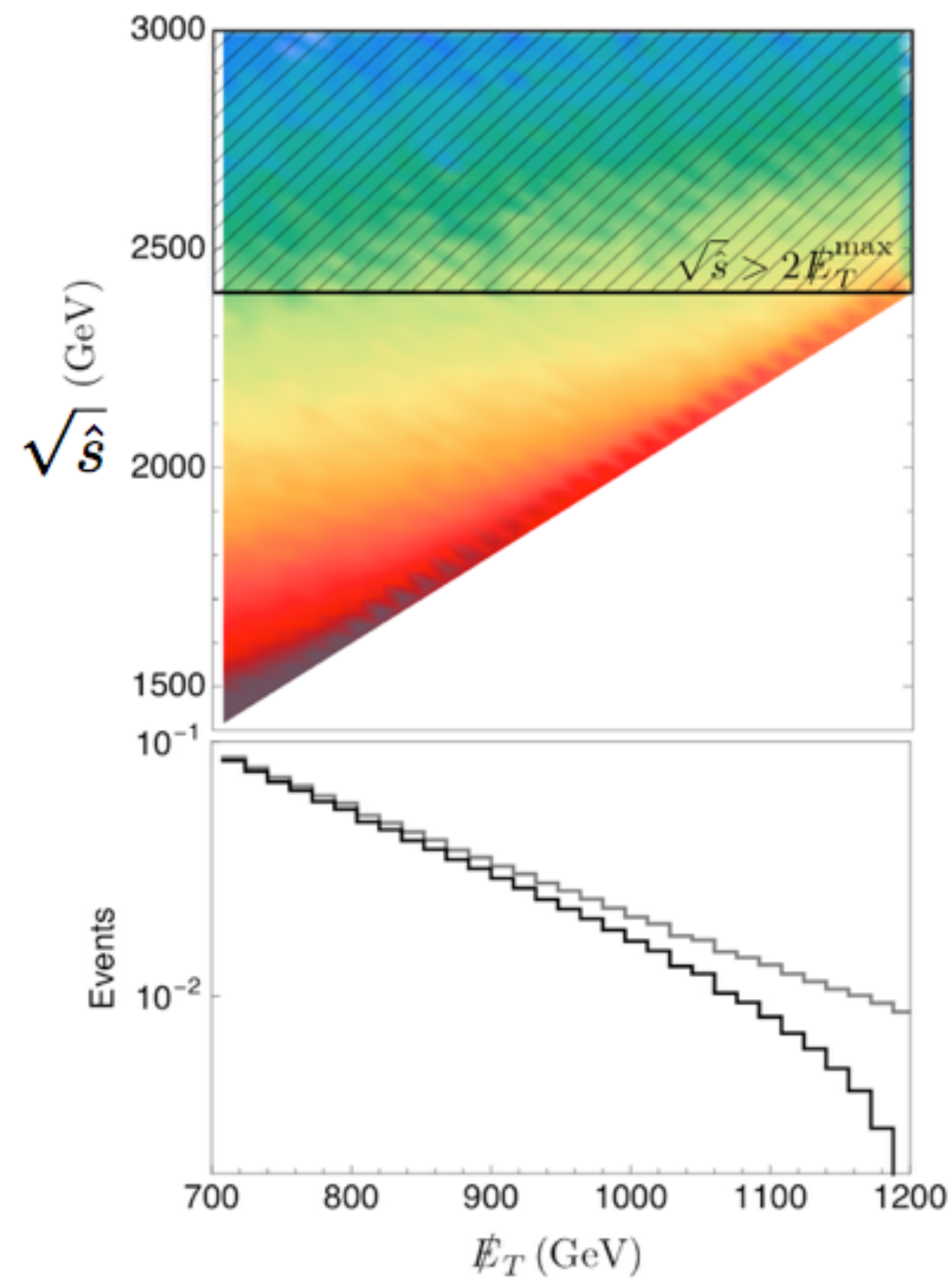
$\Rightarrow$ That analysis valid for scales $f_a > 2.4$ TeV

Is this safe, give the fact that $\boxed{m_{inv.} \geq m_T,\ \not{E}_T}$?

—> Correlation plot ————————->

Validity of the EFT, $2\,\cancel{E}_T^{max} < f_a$ vs $\sqrt{\hat{s}} < f_a$

e.g. probability density
of mono-Z events



e.g. the difference in the bounds between a cut in $2\cancel{E}_T^{max}$ and a cut in $\sqrt{\hat{s}}$ is negligible

ALP stability at the LHC vs m$_a$

e.g. for m$_a$ = 1MeV

$\underline{a \to \nu\bar{\nu}\nu\bar{\nu}}$ It would simply become part of the $\not{E}_T$ contributions

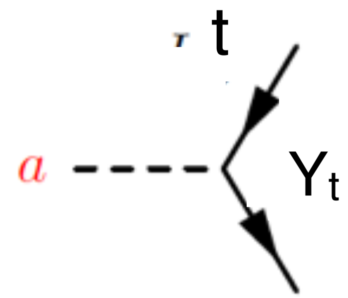
$\underline{a \to \gamma\gamma}$ The distance d covered in the laboratory frame before decaying

$$d = \tau\beta c = \frac{\hbar}{\Gamma(a)} \frac{|\vec{p}_a|}{m_a} c \quad > 4 \cdot 10^8\,\mathrm{m} \times \left(\frac{|\vec{p}_a|}{\mathrm{GeV}}\right)$$

$\underline{a \to \gamma\nu\bar{\nu}}$ ALP-Z-γ

$$d \simeq 10^{22}\,\mathrm{m} \times \left(\frac{|\vec{p}_a|/g^2_{aZ\gamma}}{\mathrm{GeV}^3}\right) > 3.3 \cdot 10^{27}\,\mathrm{m} \times \left(\frac{|\vec{p}_a|}{\mathrm{GeV}}\right)$$

Final state radiation off a top



$$\sigma(pp \to t\,\bar{t}\,a)[\sqrt{s} = 13\text{ TeV }] = c_{2D}^2 \left(\frac{1\text{ TeV}}{f_a}\right)^2 (50\text{ fb})$$

Compare with susy searches of ttbar+2 neutralinos

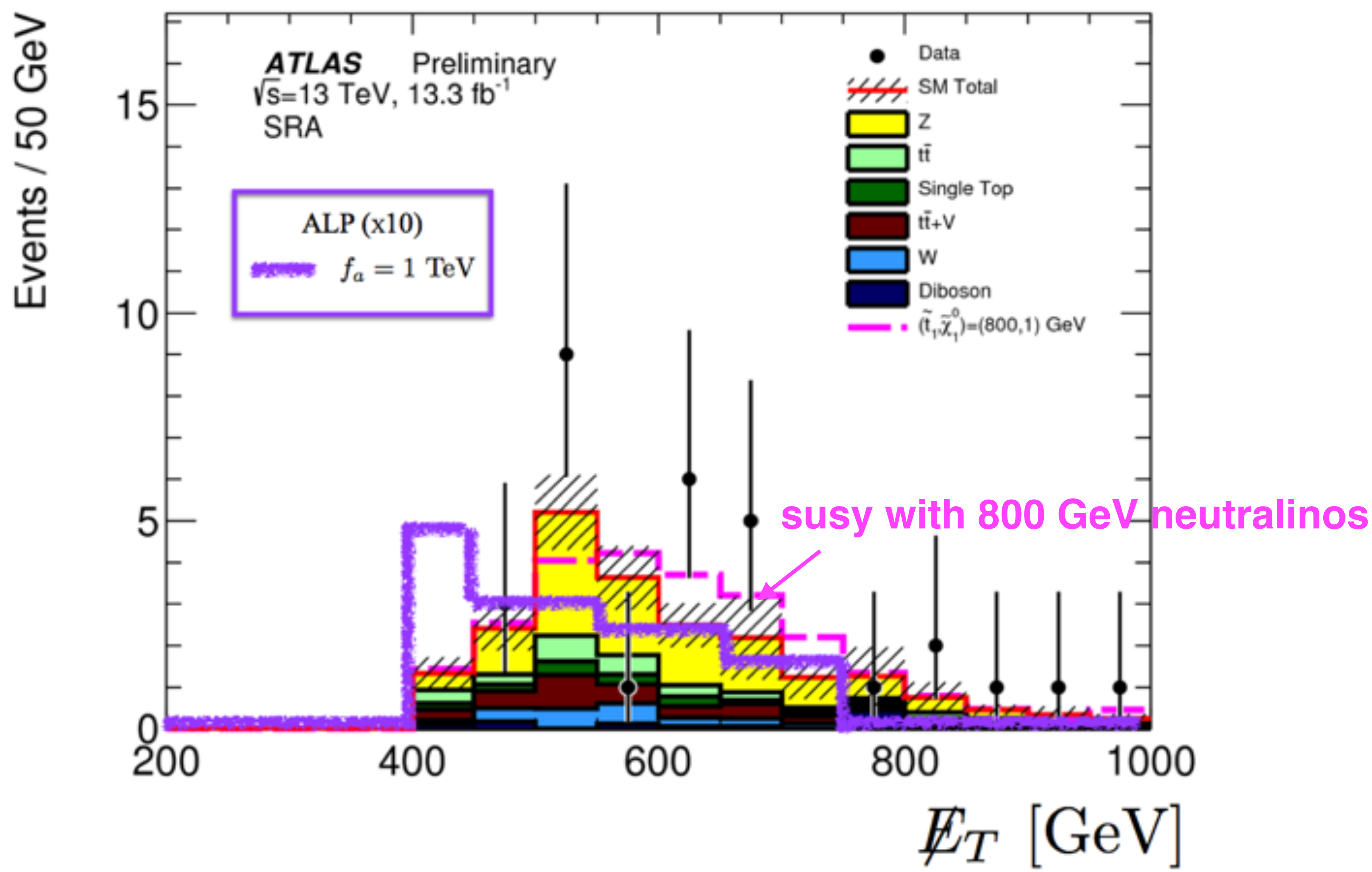


Figure 13: *Missing energy distribution for the production of an light ALP in association with $t\bar{t}$ for 13.3 fb^{-1} of 13 TeV data. The normalization has been chosen with f_a= 1 TeV and then multiplied by a factor 10. We show the corresponding simulation of supersymmetric scenarios by ATLAS, as well as their event count.*

Present exclusion limits on cW from mono-W and mono-Z

	$c_{\tilde{W}}$ (mono-W)		$c_{\tilde{W}}$ (mono-Z)	
ℓ	e	μ	e	μ
$(f_a/c_{\tilde{W}})_{\rm min}$ [TeV]	1.28	1.65	3.77	2.54
$(f_a/c_{\tilde{W}})_{\rm min}$ [TeV] [No Syst.]	1.72	2.46	3.79	2.54

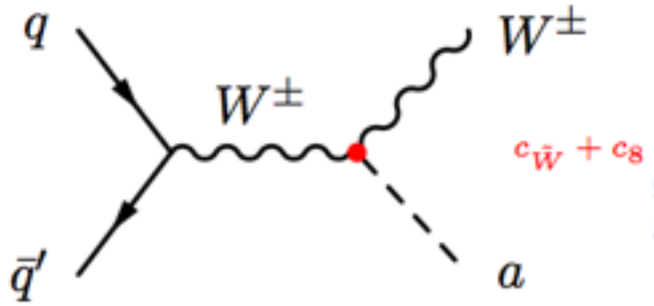
Table 3: *Present 95% C.L. $f_a/c_{\tilde{W}}$ exclusion limits for the effective operator $\mathcal{A}_{\tilde{W}}$ from mono-W (left), inferred from the search presented in Ref, [98] as detailed in Sect. 6.3.1 and mono-Z (right) inferred from the search presented in Ref. [100] as detailed in Sect. 7.1.1. Values obtained without including background systematics are labeled [No Syst.].*

Prospects on cW from mono-Z

	$c_{\tilde{W}}$ (mono-Z)			
ℓ	e		μ	
Luminosity [fb^{-1}]	300	3000	300	3000
f_a/c_i [TeV]	10.5	15.87	9.77	14.37
f_a/c_i [TeV] [Syst.×1/2]	11.14	18.45	10.38	16.7
f_a/c_i [TeV] [No Syst.]	11.68	21.5	10.9	19.66

Table 4: *Projected 95% C.L. f_a/c_i reach at LHC, with $\mathcal{L}$ = 300 fb^{-1} and $\mathcal{L}$ = 3000 fb^{-1} for $\mu_{\tilde{W}} = (c_{\tilde{W}}/f_a)^2$ for the effective operators relevant to mono-Z production, as detailed in Sect. 6.3.2. Top row: Assuming future systematic uncertainties on the background scale as present ones. Middle row: Assuming systematic uncertainties are reduced by a factor 2 w.r.t. present ones. Bottom row: Assuming no background systematic uncertainties.*

Mono-W



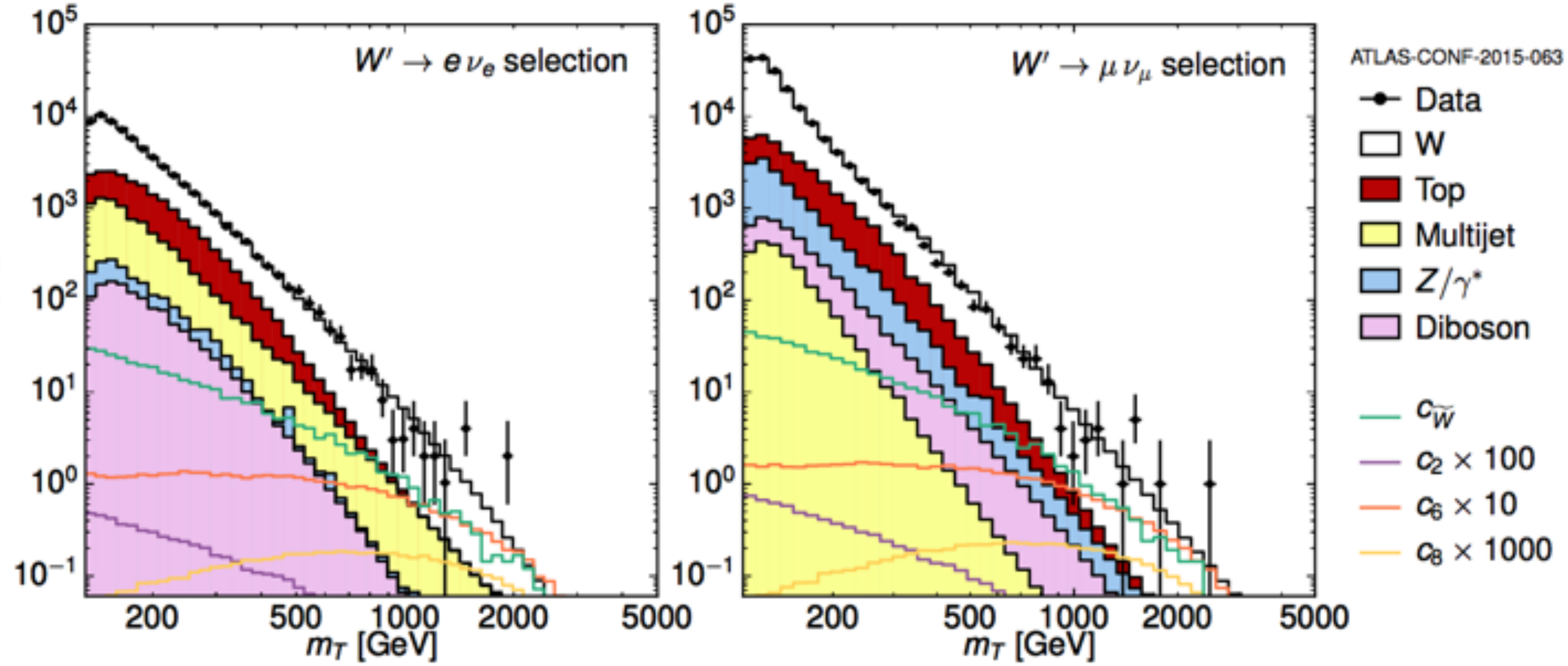


Figure 3: *Transverse mass m_T distribution for a $W^\pm$ ($W^\pm \to \ell^\pm \nu_\ell$) production in the $e + \not{E}_T$ final state (Left) and $\mu + \not{E}_T$ final state (Right), generated from $\mathcal{A}_{\tilde{W}}$ (green), $\mathcal{A}_2$ (purple), $\mathcal{A}_6$ (orange) and $\mathcal{A}_8$ (yellow). Also shown are the binned experimental data and dominant backgrounds from the 13 TeV* ($3.3\,\text{fb}^{-1}$) *ATLAS analysis [98].*

	c_6 (mono-W)		$c_{\tilde{W}}$ (mono-W)	
Luminosity [fb^{-1}]	300	3000	300	3000
f_a/c_i [TeV]	2.09	2.71	1.90	2.32
f_a/c_i [TeV] [Syst.×1/2]	2.35	3.44	2.29	3.01
f_a/c_i [TeV] [No Syst.]	2.60	4.68	3.43	6.10

Table 5: *Projected 95% C.L. f_a/c_i LHC reach for $\ell = e$ final states, with $\mathcal{L} = 300\ \text{fb}^{-1}$ and $\mathcal{L} = 3000\ \text{fb}^{-1}$ for the effective operators relevant to mono-W production, as detailed in Sect. 6.3.1. Top row: Assuming future systematic uncertainties on the background scale as present ones. Middle row: Assuming systematic uncertainties are reduced by a factor 2 w.r.t. present ones. Bottom row: Assuming no background systematic uncertainties.*

Associated aWγ

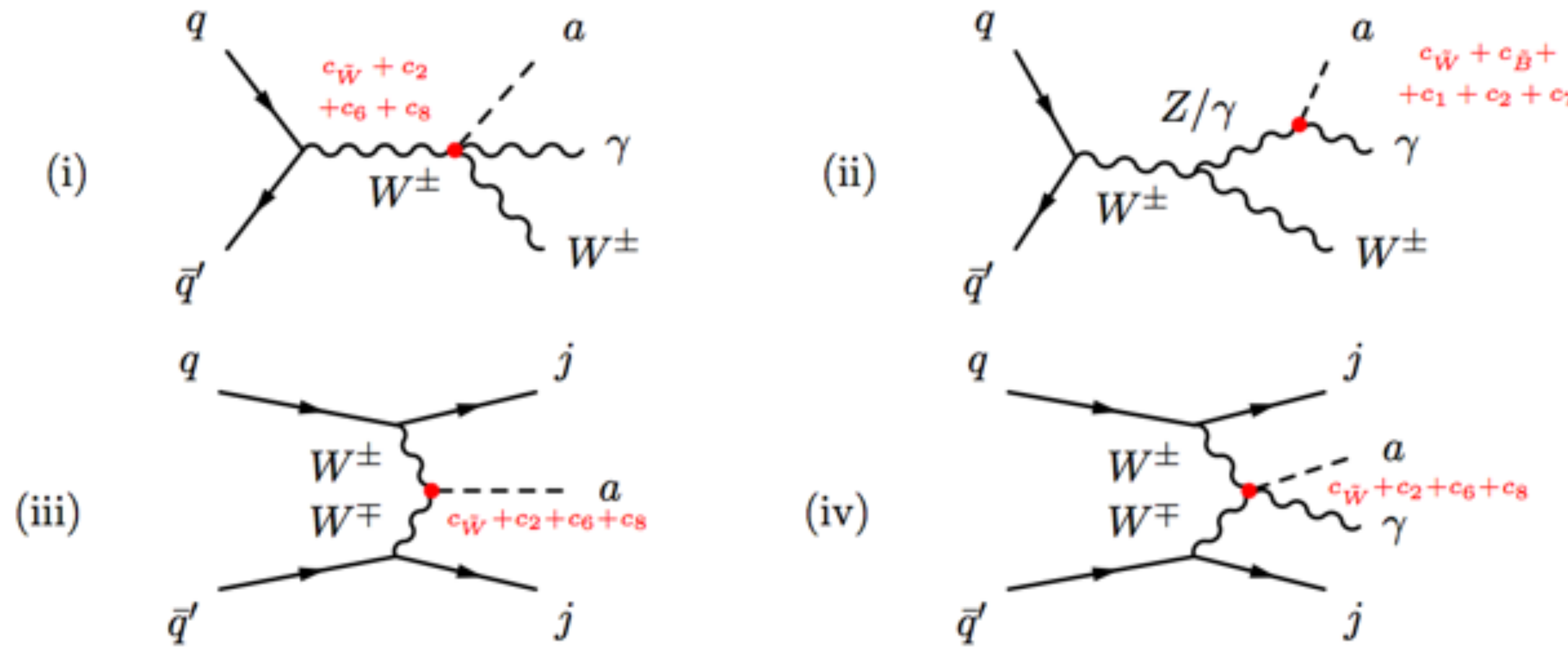


Figure 5: *Main diagrams contributing to the processes analysed in Sect. 7.2. Upper line: $a\gamma W$ associated production. Lower line: VBF-type interaction producing ajj (iii) and $ajj\gamma$ (iv). The proportionality of each diagram to the non-linear parameters is indicated in the figure (overall factors and relative coefficients are not displayed).*

	c_6		$c_{\tilde{W}}$	
Luminosity [fb^{-1}]	300	3000	300	3000
Optimal $\not{E}_T^{\min}$ [GeV]	300	330	220	220
$(f_a/c_i)_{\max}$ [GeV]	470	950	3800	6800

Table 6: *Optimal missing transverse energy cut $\not{E}_T^{min}$, and $(f_a/c_i)_{\max}$ 2σ projected sensitivity reach for $aW\gamma$ production, for $\sqrt{s} = 13$ TeV and integrated luminosities 300 fb^{-1} and 3000 fb^{-1}.*

Associated aWγ

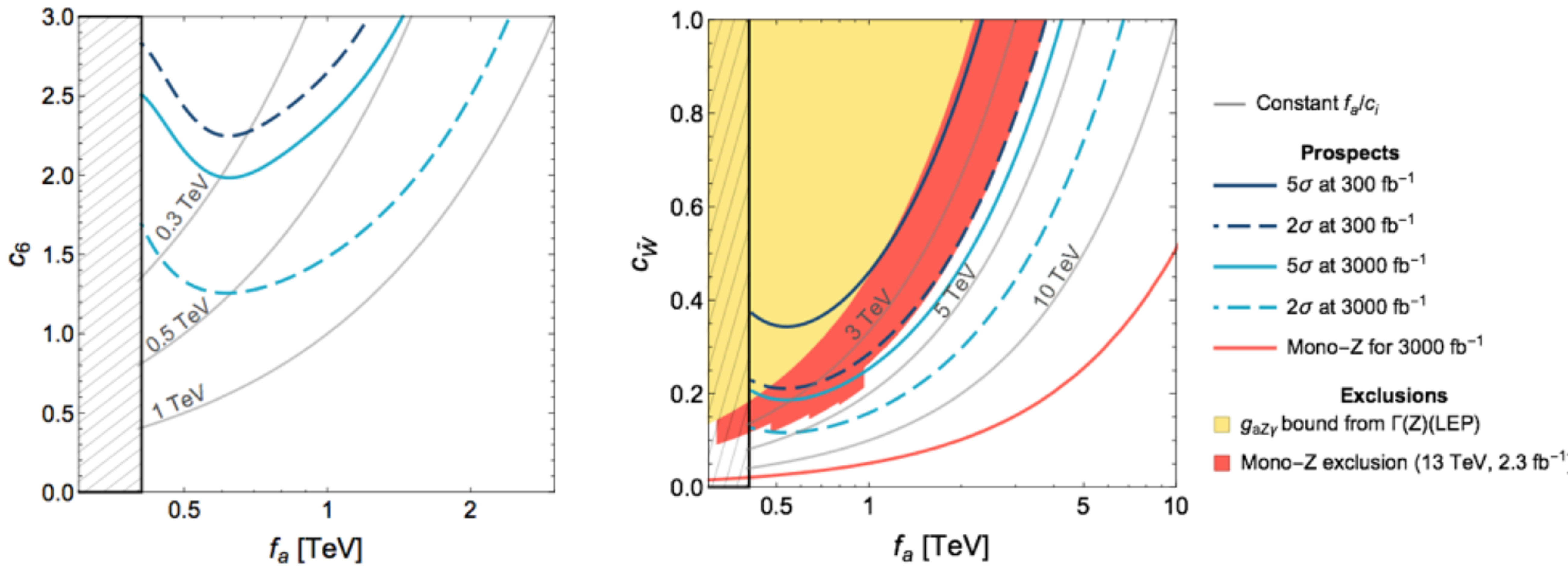
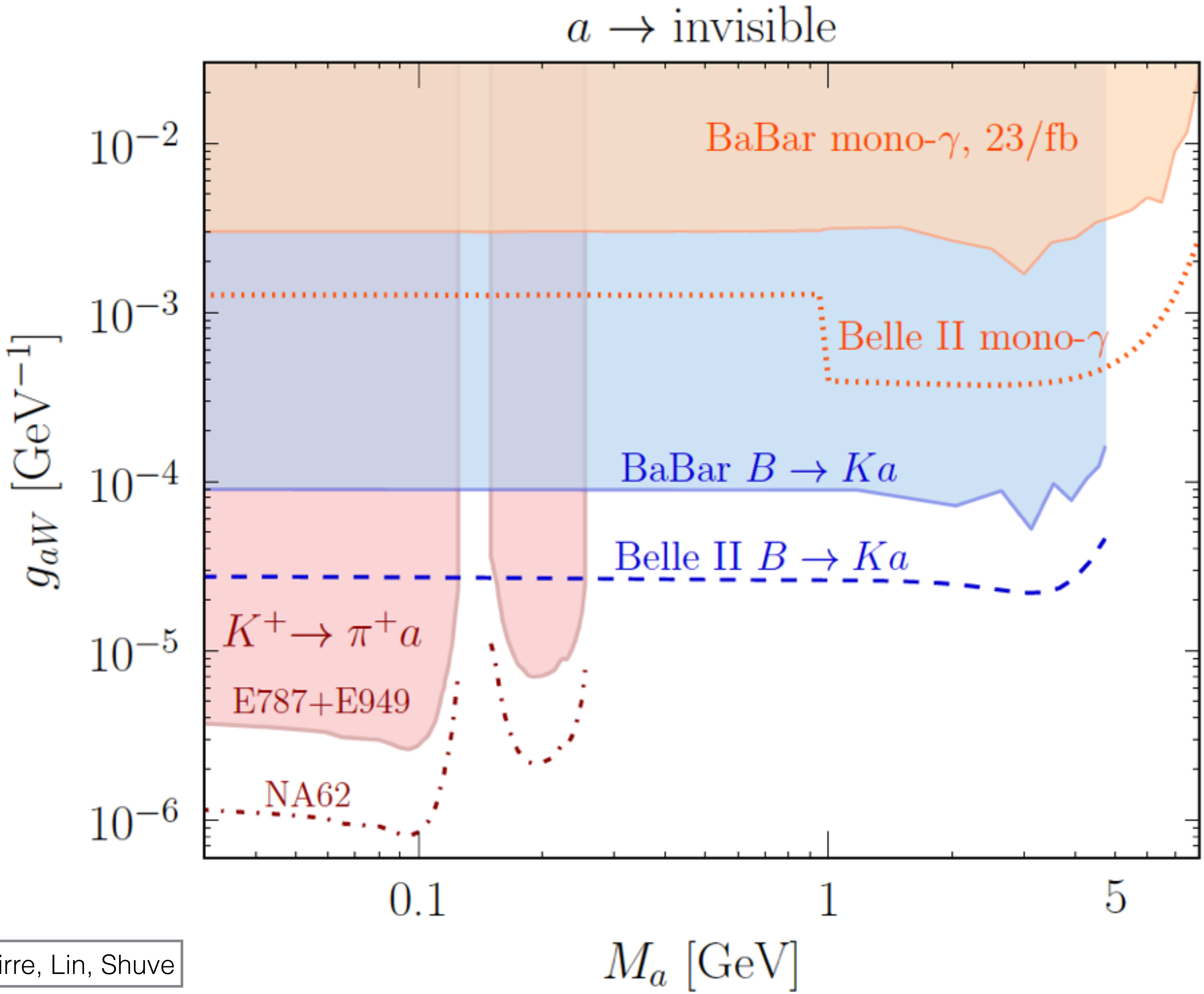


Figure 8: *Contours for $\sigma = 2$ (dashed) and $\sigma = 5$ (solid) sensitivity to $pp \to aW^{\pm}\gamma$ ($W^{\pm} \to \ell^{\pm}\nu$) signal at the LHC with $\sqrt{s} = 13\,\mathrm{TeV}$ and for an integrated luminosity of $300\,\mathrm{fb}^{-1}$ (dark blue) and $3000\,\mathrm{fb}^{-1}$ (light blue), as a function of $\{f_a, c_i\}$. The left (right) panel shows the results obtained assuming that only the operator $\mathcal{A}_6$ (the combination of operators $(\mathcal{A}_{\tilde{W}} - t_\theta^2 \mathcal{A}_{\tilde{B}})$) is contributing. The hatched region corresponds to $f_a < 2\not{E}_T^{\rm min}$, and is excluded by the EFT validity. The yellow region is excluded by the bound on $g_{aZ\gamma}$ reported in Eq. (125). The mono-Z exclusion region from $\sqrt{s} = 13\,\mathrm{TeV}$ LHC with $2.3\,\mathrm{fb}^{-1}$ of data is depicted by the red region. The gray reference lines correspond to constant values of f_a/c_i. The region*

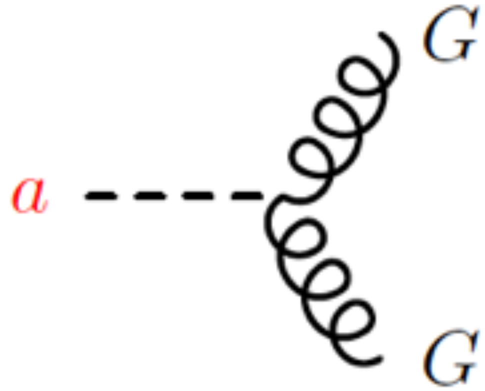
Main backg.: Wγ, measured in LHC 7TeV. scaled here by 20% to account for subdominant backs.

Parton level analysis. $p_T^{\gamma} > 20\,\mathrm{GeV}$, $p_T^{\ell} > 20\,\mathrm{GeV}$, $|\eta^{\gamma}| < 2.5$ and $|\eta^{\ell}| < 2.5$

Sensitivity reach: $f_a/c_{\tilde{W}} \lesssim 3.8\ \mathrm{TeV}\ (6.8\ \mathrm{TeV})$ $\quad f_a/c_6 \lesssim 0.4\ \mathrm{TeV}\ (0.8\ \mathrm{TeV})$



Izaguirre, Lin, Shuve



Present bounds on gluon-ALP couplings

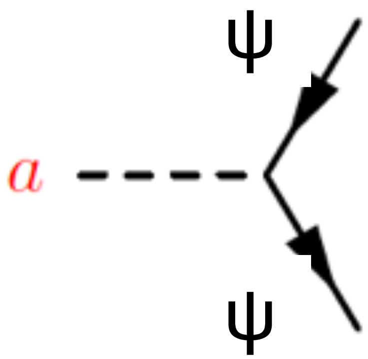
$$\mathcal{A}_{\tilde{G}} \;=\; -G^{a}_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

ATLAS+CMS:
(Mimasu+Sanz, 2015)

$$\frac{c_{\tilde{G}}}{f_a} \lesssim 2.5\;10^{-5}\,\mathrm{GeV}^{-1} \qquad m_a \lesssim 0.1\,\mathrm{GeV}$$

K—>π, SN, etc…

$$\frac{c_{\tilde{G}}}{f_a} \lesssim 2.8\;10^{-6}\,\mathrm{GeV}^{-1} \qquad m_a \lesssim 60\,\mathrm{MeV}$$



Present bounds on fermion-Alp couplings

$$\delta\mathscr{L}_a \supset \frac{ia}{f_a}\sum_{\psi=Q,\,L} g_{a\psi}\, m_\psi^{\mathrm{diag}}\,\bar{\psi}\gamma_5\psi$$

Beam Dump:
(Dolan et al. 2014)

$$g_{a\psi}/f_a < \left(3.4\cdot 10^{-8} - 2.9\cdot 10^{-6}\right)\;\mathrm{GeV}^{-1} \quad 1\,\mathrm{MeV} \lesssim m_a \lesssim 3\,\mathrm{GeV}$$

XENON100:
(Aprile et al. 2014)

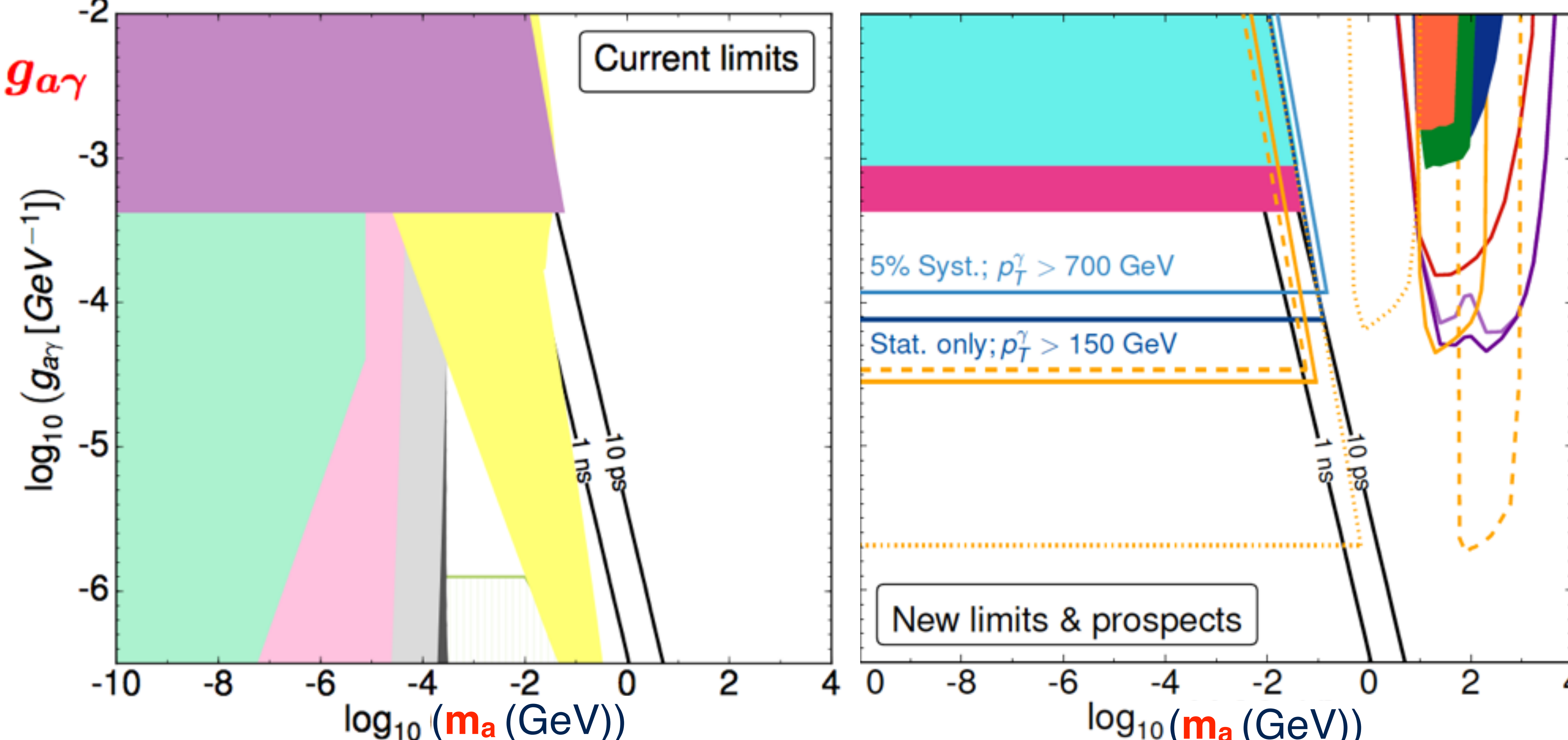
$$g_{ae}/f_a < 1.5\cdot 10^{-8}\,\mathrm{GeV}^{-1} \qquad m_a < 1\,\mathrm{keV}$$

Red Giants:
(Viaux et al. 2013)

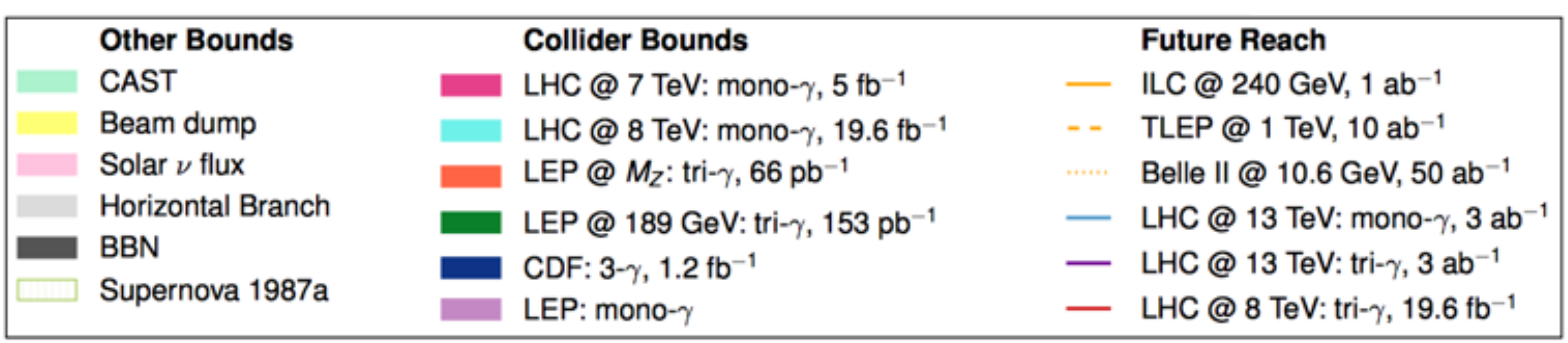
$$g_{ae}/f_a < 8.6\cdot 10^{-10}\,\mathrm{GeV}^{-1} \qquad m_a \lesssim \mathrm{eV}$$

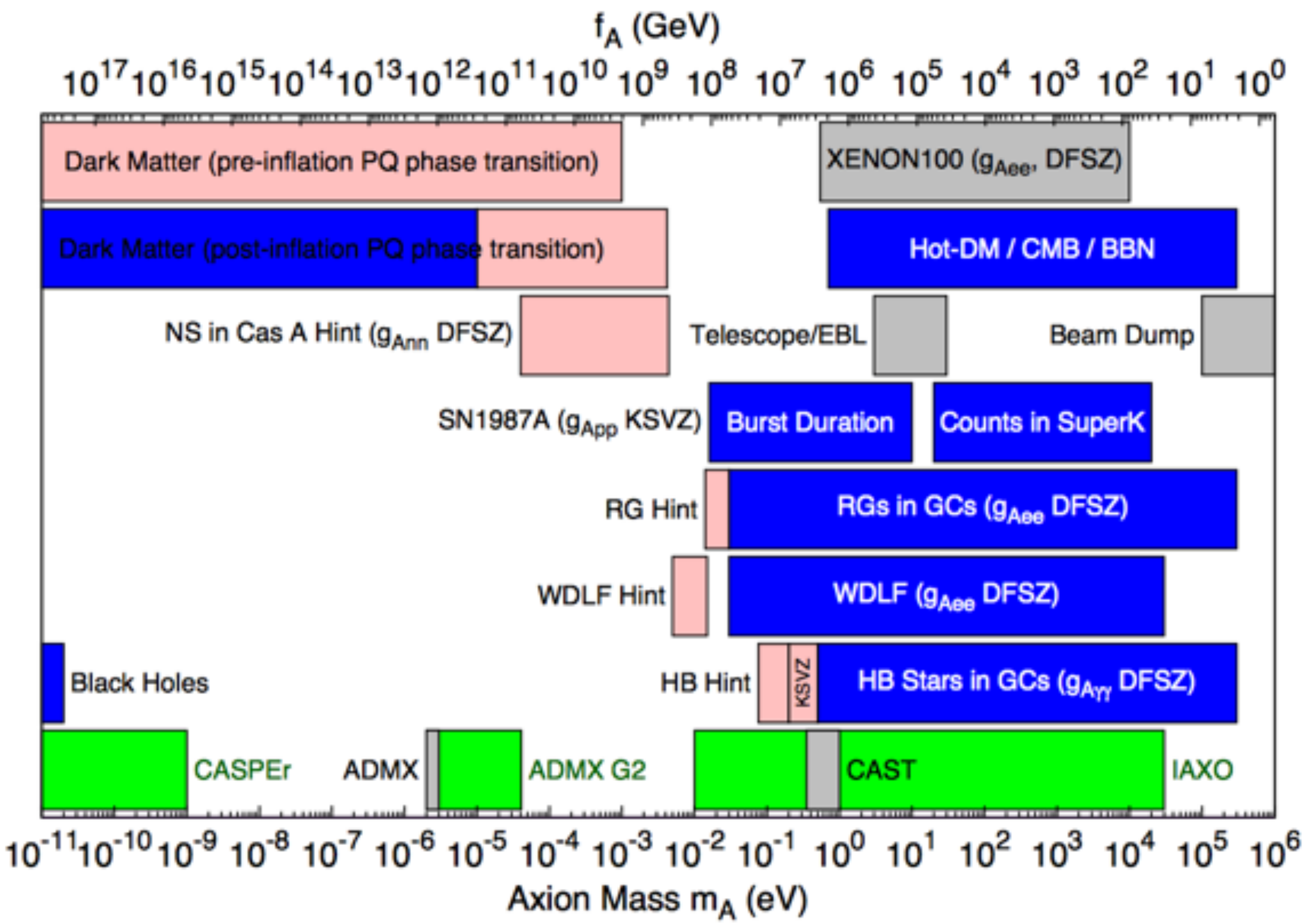
Bounds on photon-ALP coupling

e.g. 90% CL: $|c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2| \lesssim \begin{cases} 0.0025\ (f_a/\mathrm{TeV}) & m_a \leq 1\,\mathrm{MeV} \\ 2.5 \cdot 10^{-8}\ (f_a/\mathrm{TeV}) & m_a \leq 1\,\mathrm{keV} \end{cases}$



Mimasu+Sanz 2015





xclusion ranges as described in the ervals in the bottom row are the approximate ADMX, CASPEr, CAST, and IAXO search ranges, with green regions indicating the projected reach. Limits on coupling strengths are translated into limits on m_A and f_A using $z = 0.56$ and the KSVZ values for the coupling strengths, if not indicated otherwise. The "Beam Dump" bar is a rough representation of the exclusion range for standard or variant axions. The limits for the axion-electron coupling are determined for the DFSZ model with an axion-electron coupling corresponding to $\cos^2\beta' = 1/2$.