News on ALPs

Belén Gavela
Univ. Autónoma de Madrid and IFT

ALPS 2017

H2020 elusives invisiblesPlus

We will consider the SM plus a generic scalar field a

with derivative couplings to SM particles

and free scale $\mathbf{f}_a$:

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: $a \to a + {\rm cte.}$ ➡ **~ Goldstone boson**

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

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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

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The nature of DM is unknown

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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$$\mathcal{L}_{QCD} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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In “true QCD axion” models: $\mathbf{m}_a \mathbf{f}_a$ = cte.

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)

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

$\Lambda \gg m_q$: $m_q < \bar{\Psi}\Psi > \simeq m_\pi^2 f_\pi^2$

QCD

$\Lambda \ll m_q$: Λ^4

Choi et al. 1986

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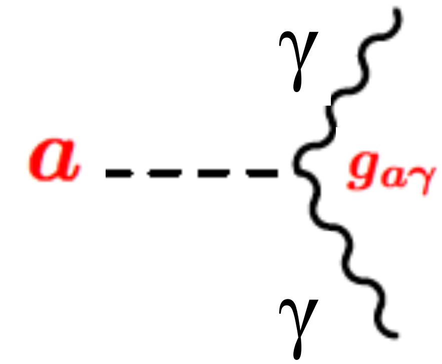
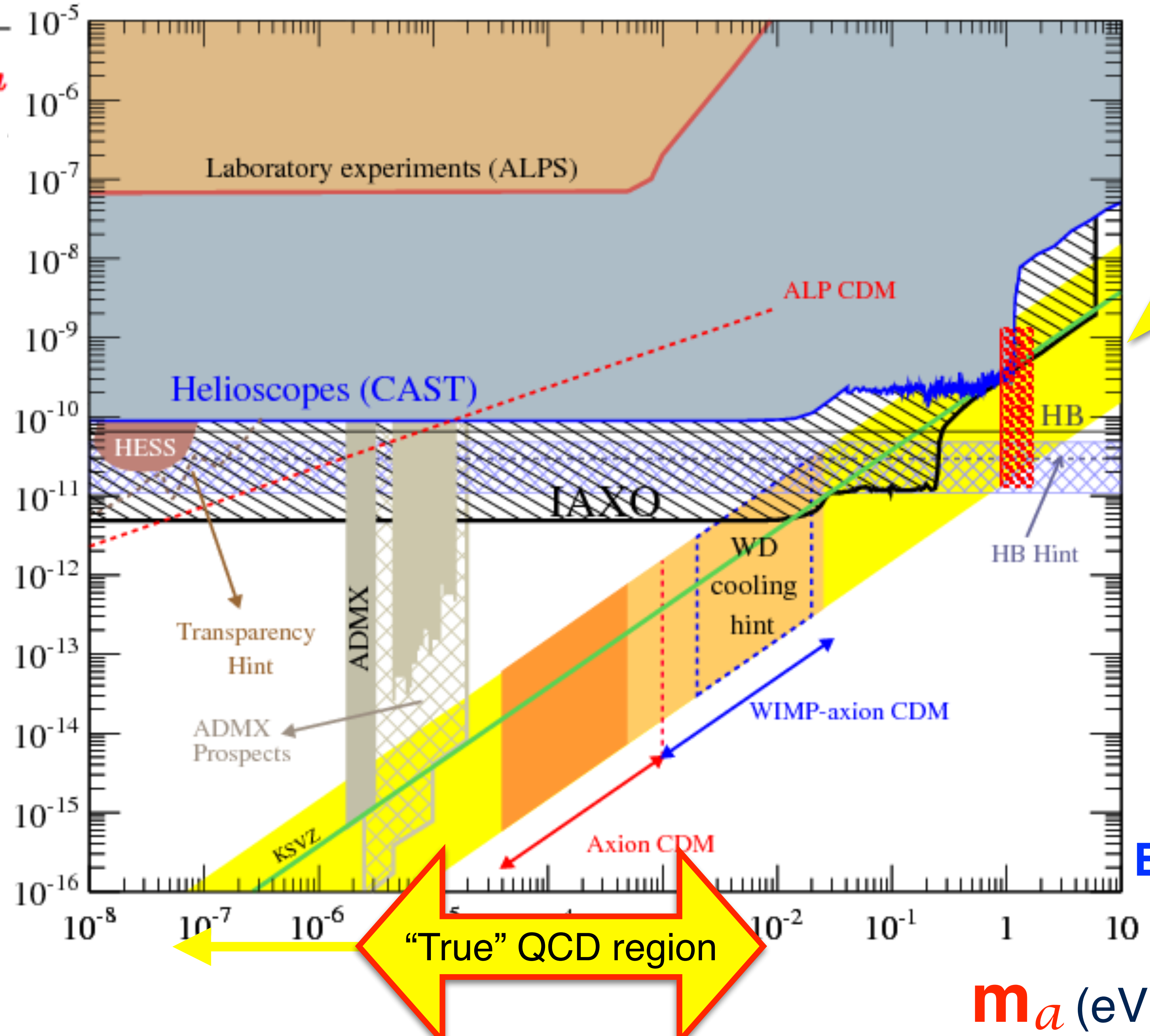


$$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$$

(GeV^{-1})



m_a (eV)

"True" QCD axion band

=

"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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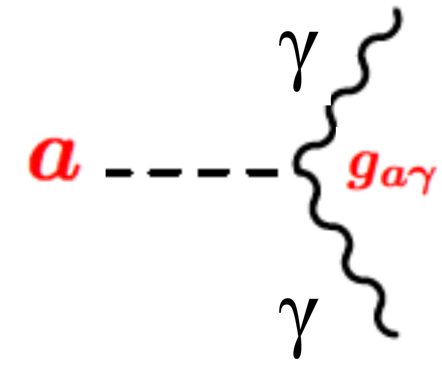

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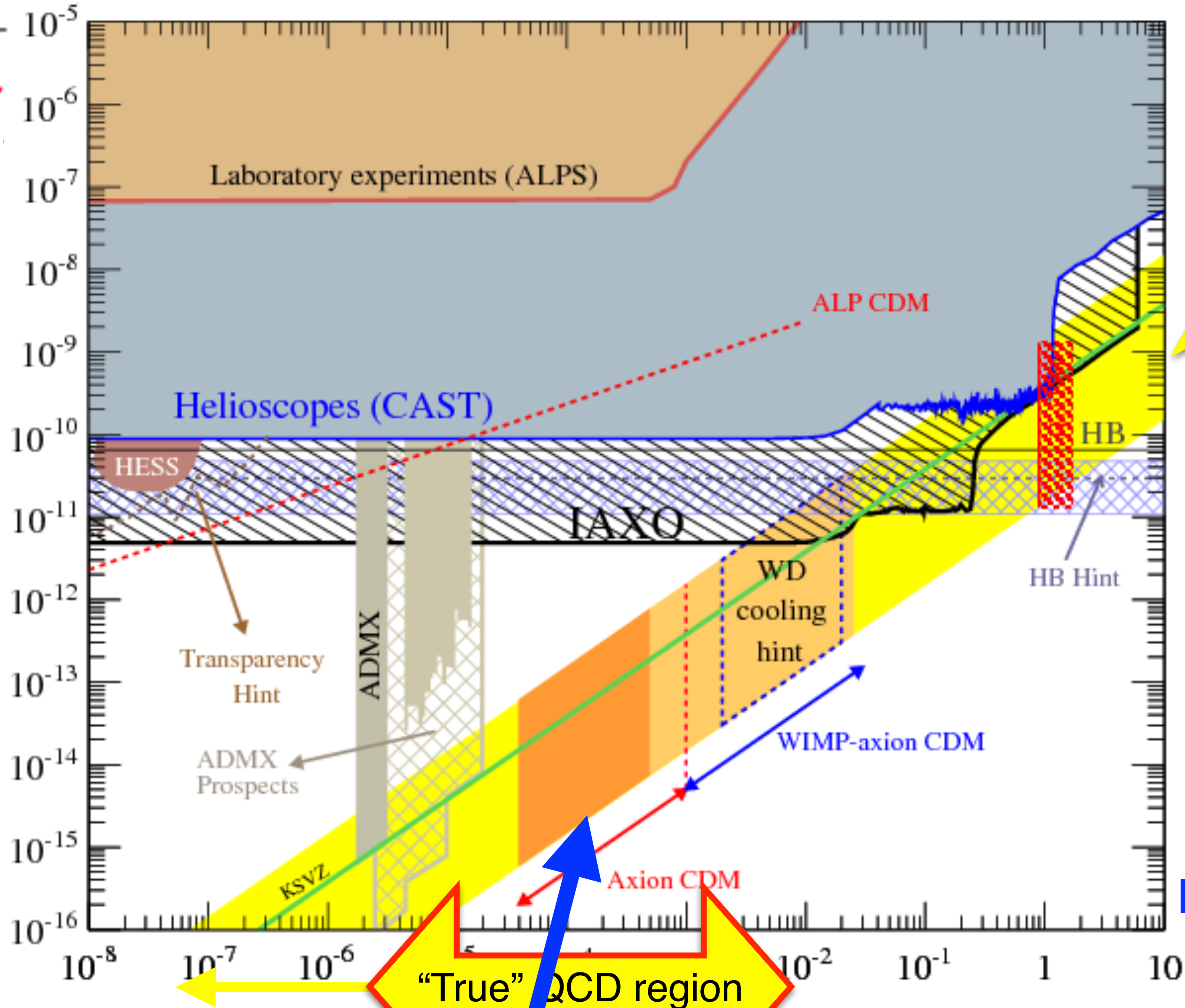

"True" QCD region

"True" QCD axion band

II

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EW hierarchy problem

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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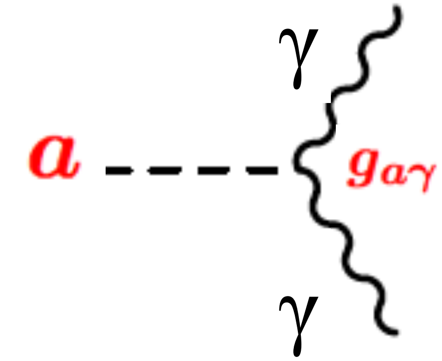

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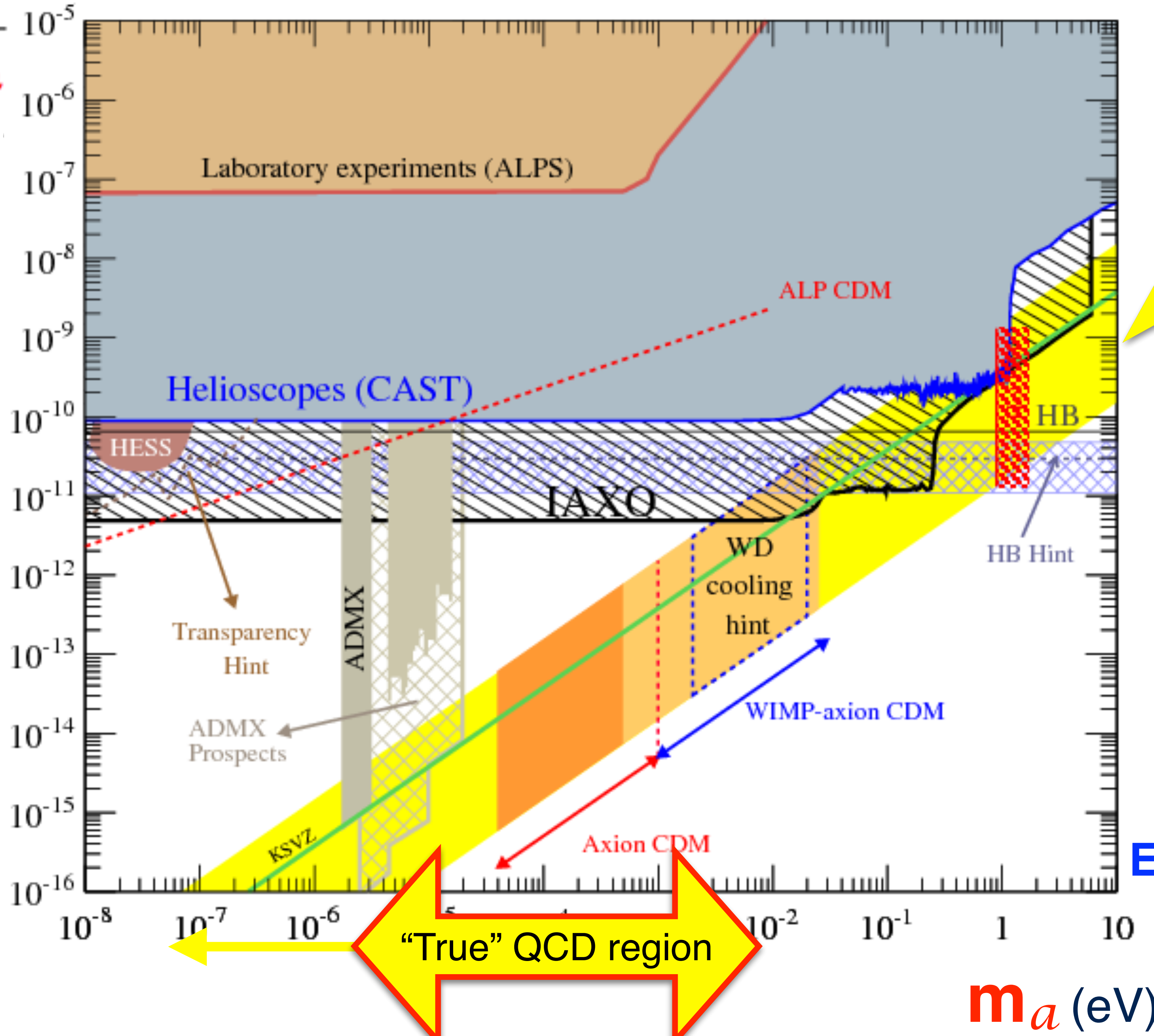

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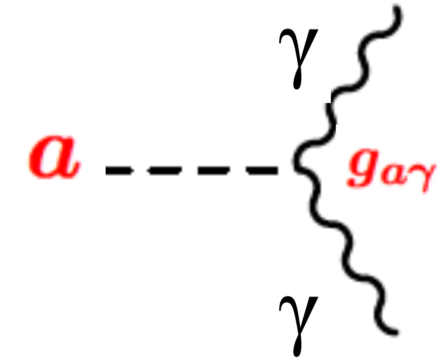

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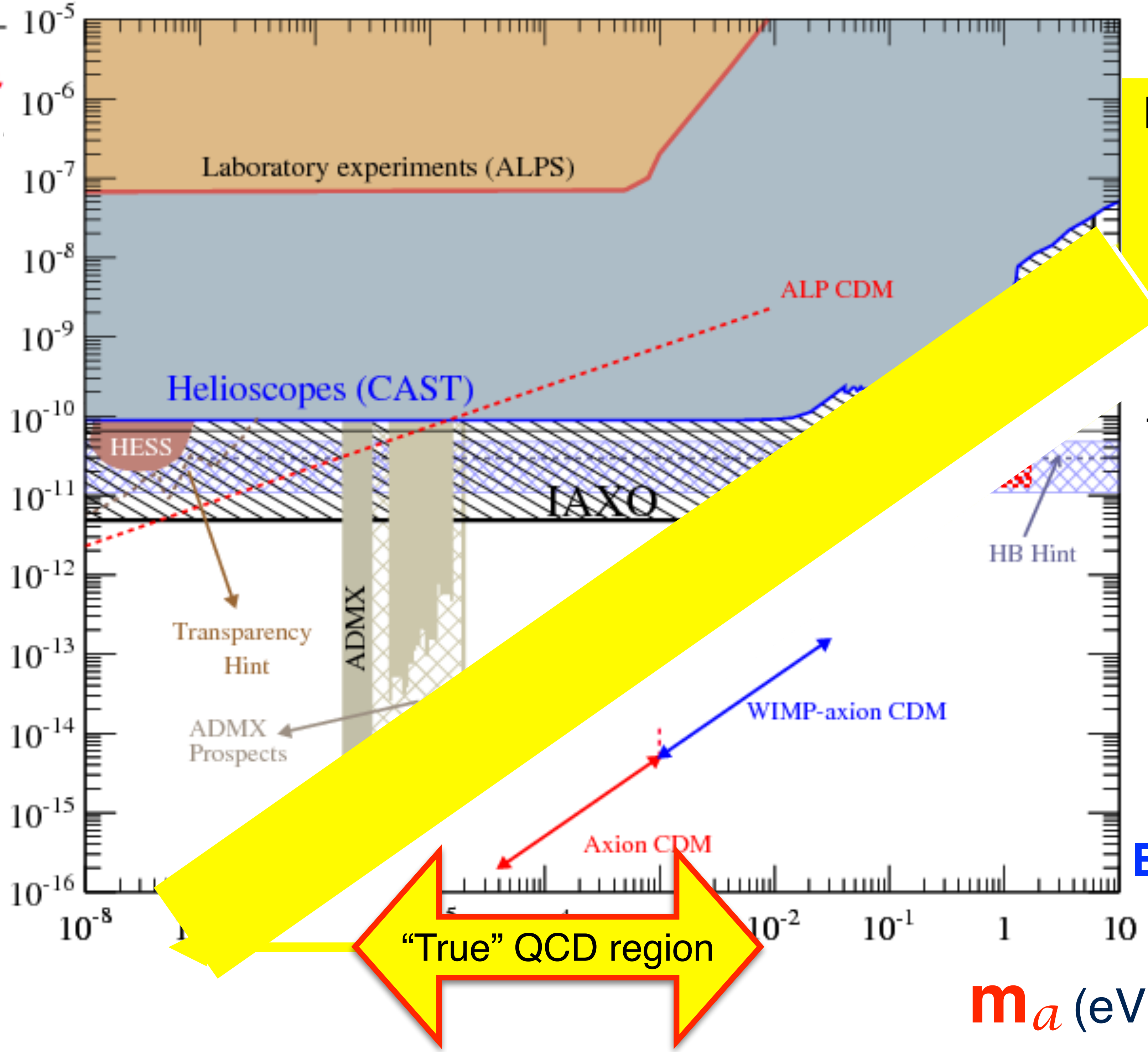

m_a (eV)

Refined KSVZ axion band: up and thinner

from Ω_{DM}
+ Landau-poles analysis

(Luzio+Mescia+Nardi 2017)

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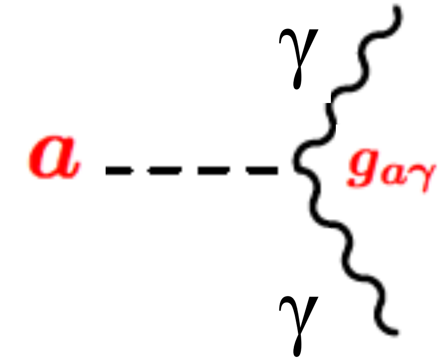

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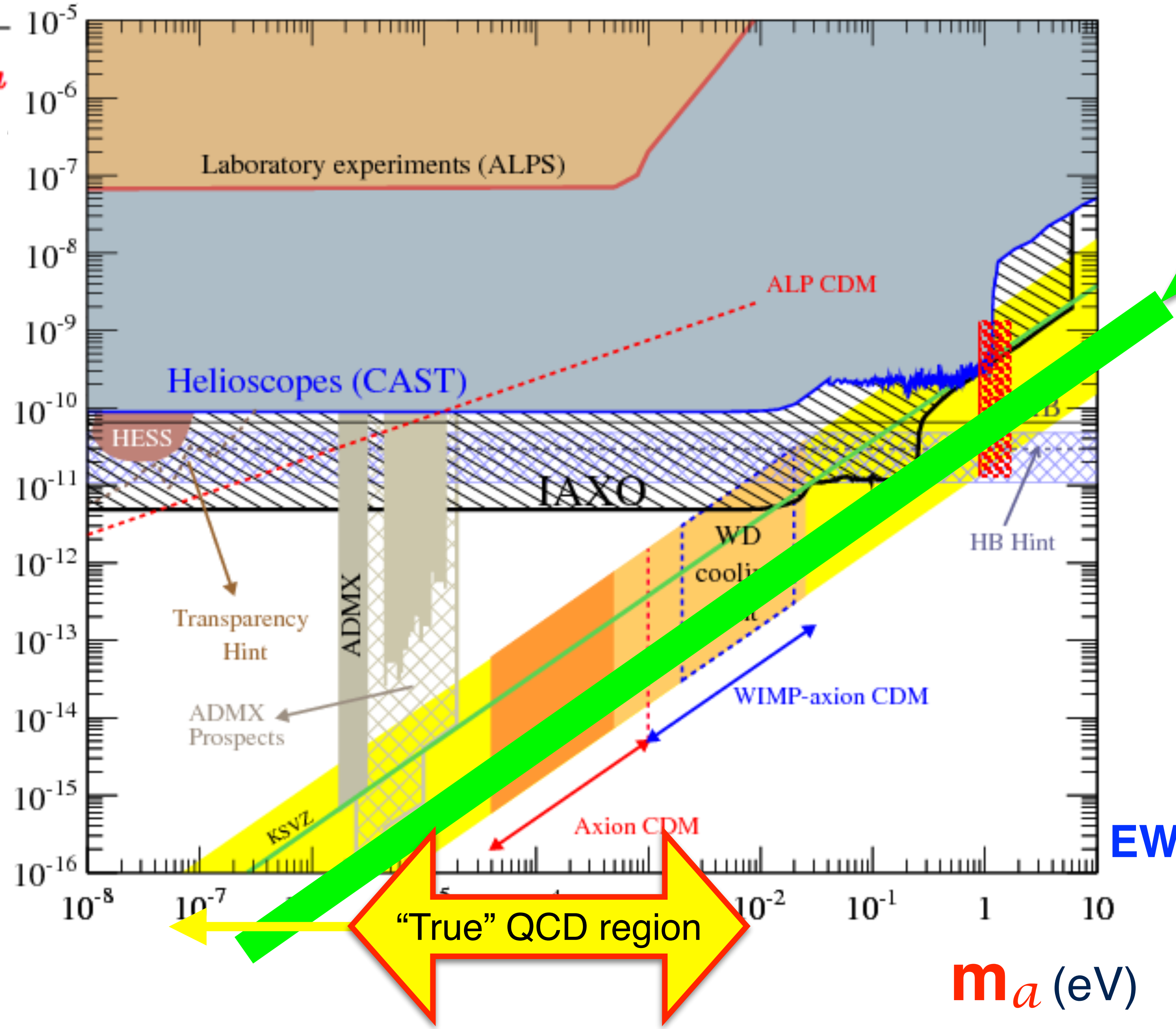

QCD axiflavon band
(creative view)

(Calibbi et al. 2016)

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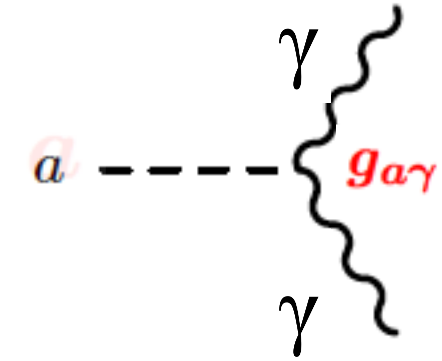

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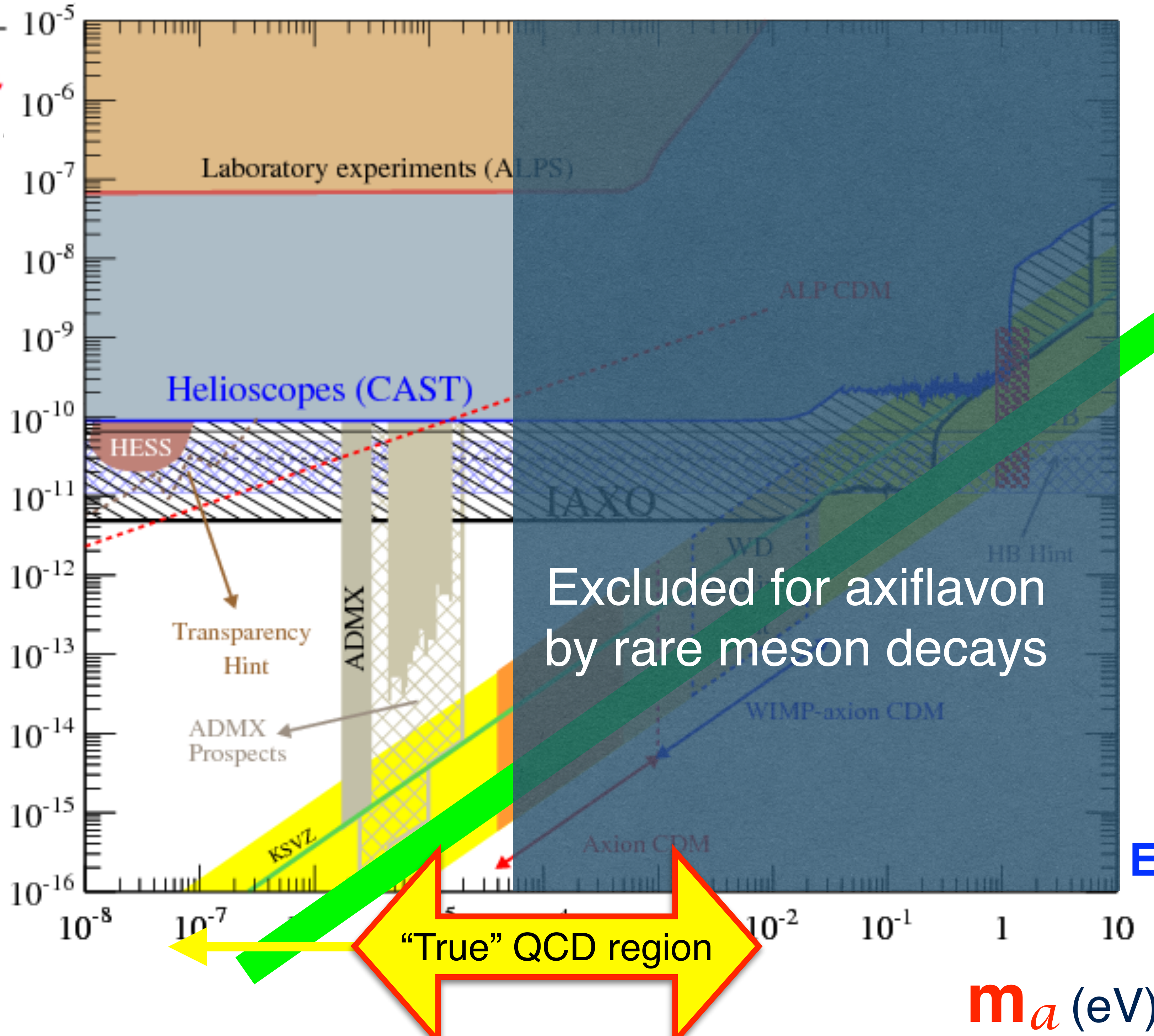

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* **Models enlarging the strong SM gauge sector**, with scale **Λ' ?**

$$m_a^2 f_a^2 = \text{QCD part} + \Lambda'^4 \quad , \quad \Lambda' \gg \Lambda_{QCD}$$

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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…

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

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

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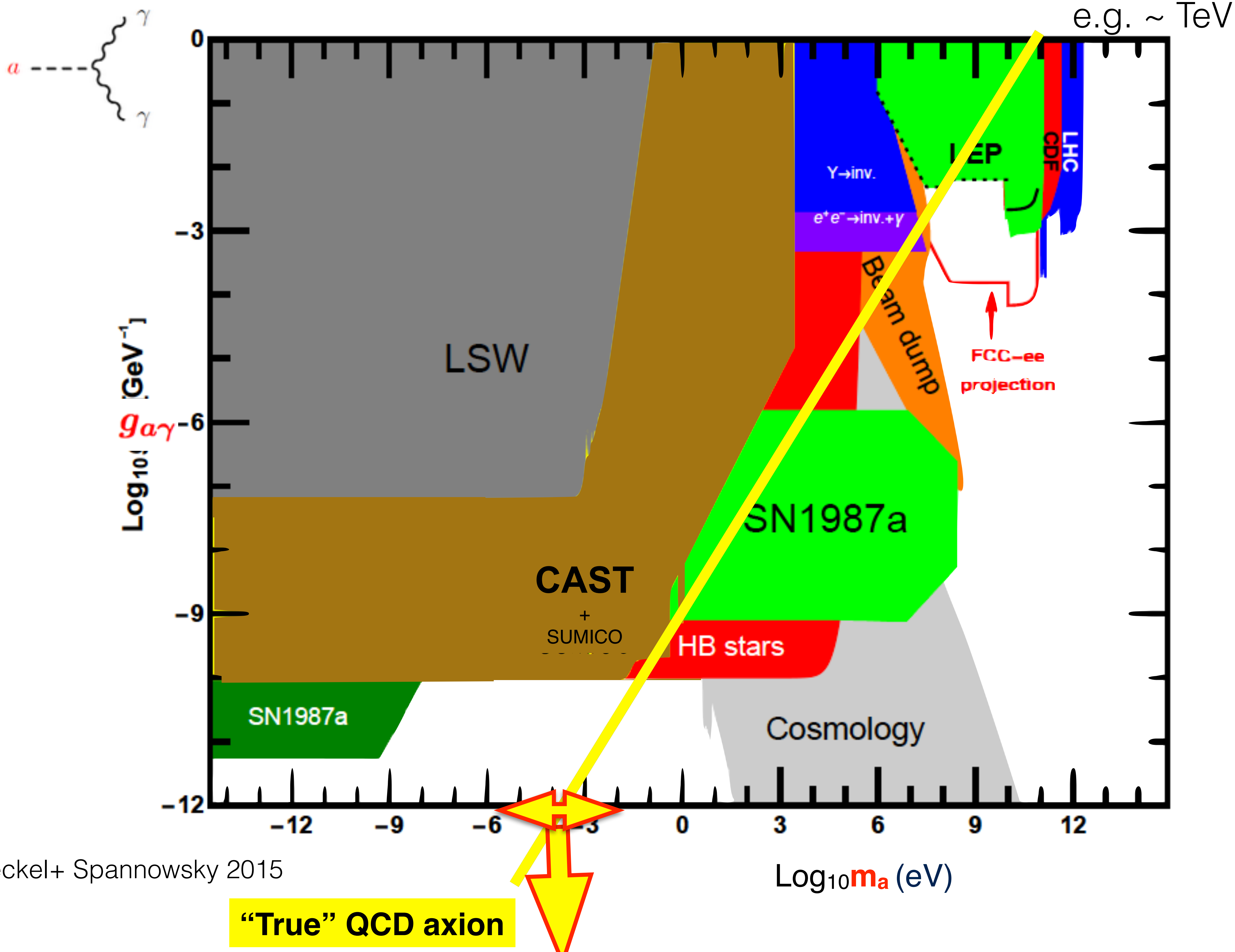
* **The ugly part:** **θ** **and** **θ'**

—>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 ~ TeV**, **m_a ~ 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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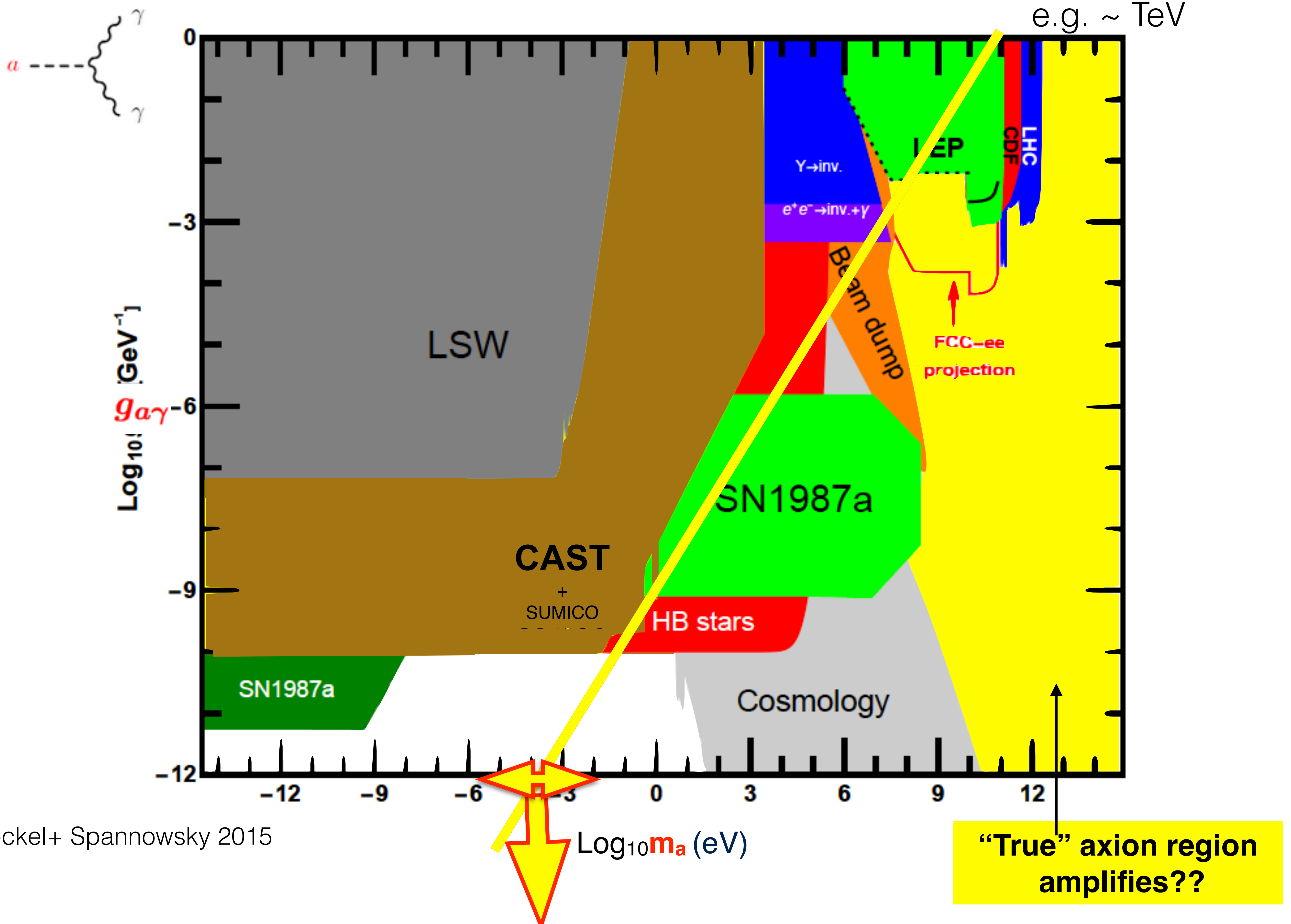

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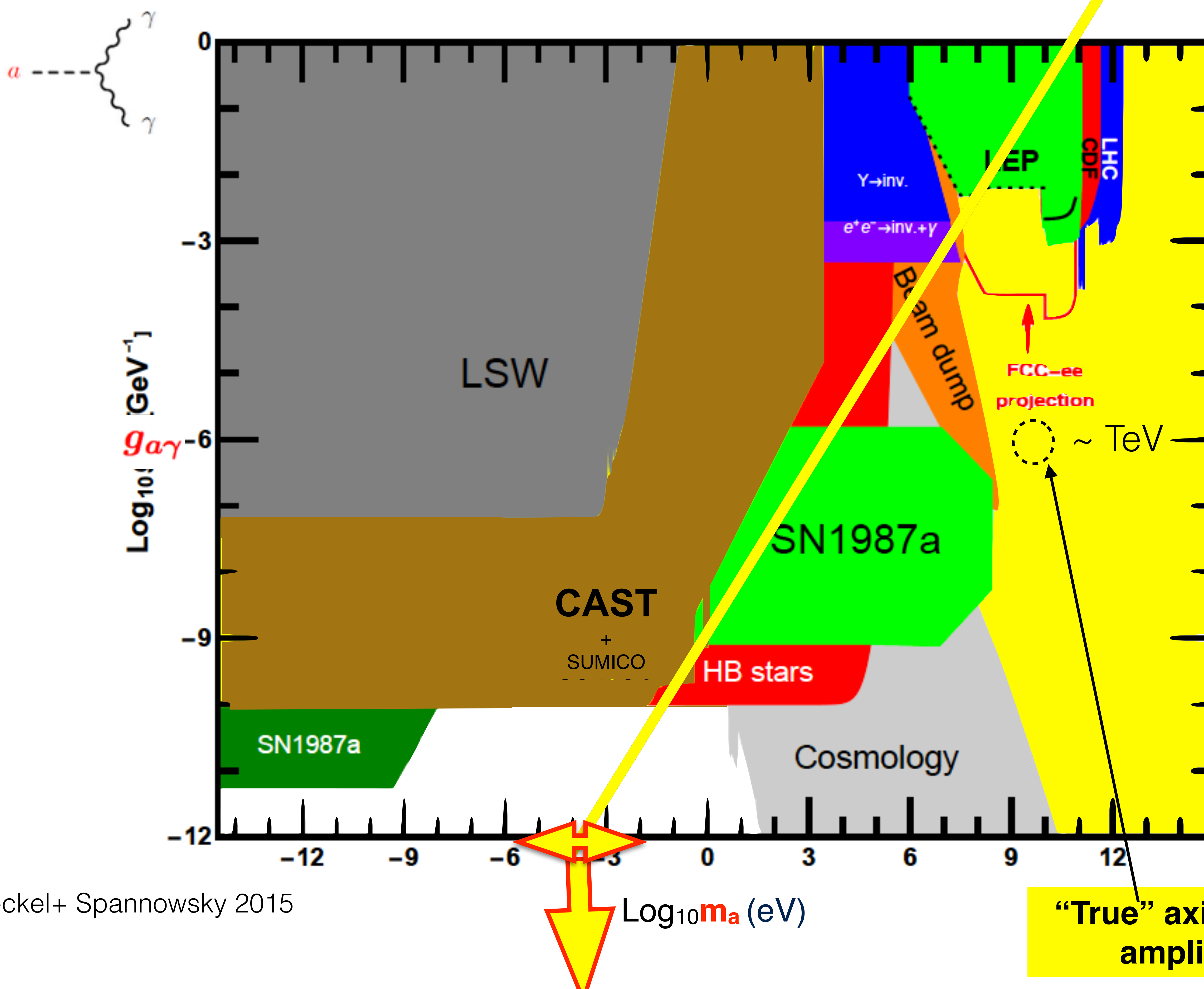
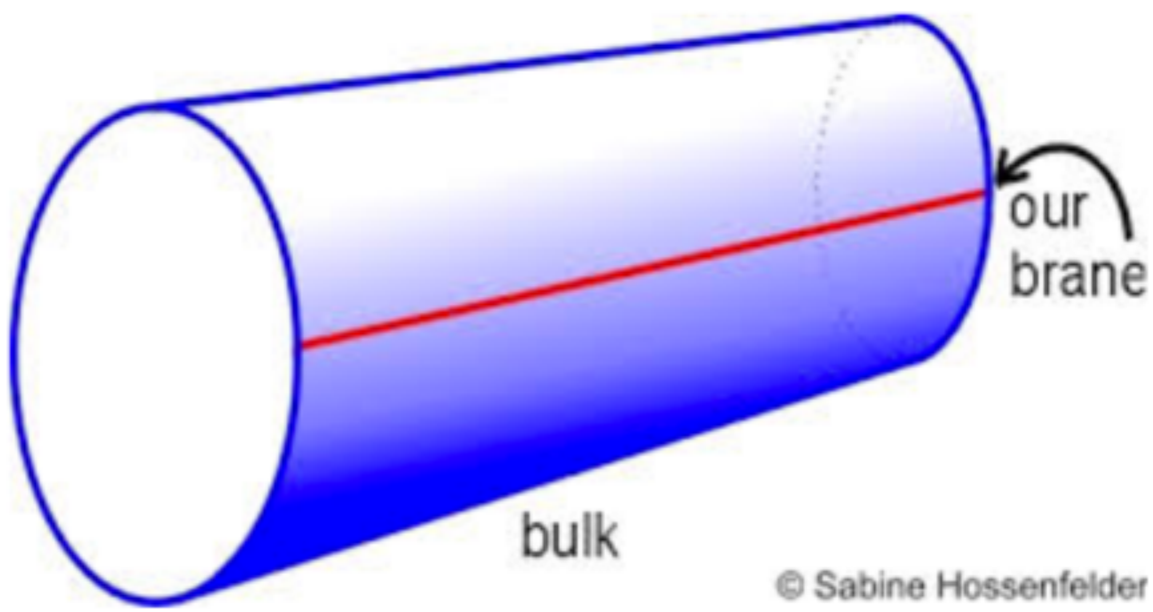


Jaeckel+ Spannowsky 2015

"True" axion region amplifies??

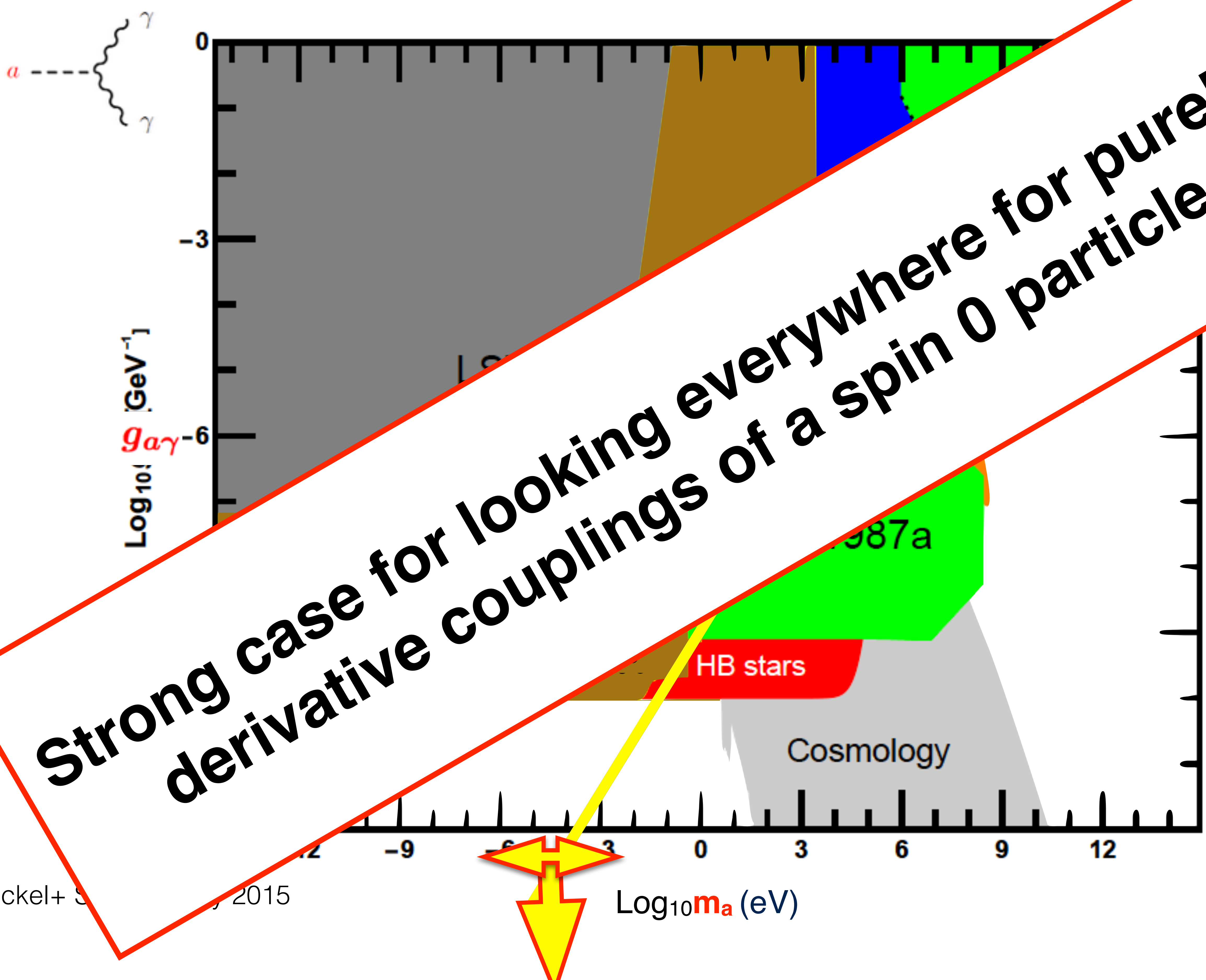
(Pseudo)Goldstone Bosons also in many BSM theories

* 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



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

* Much territory to explore for axions and ALPs



Jaeckel+ S... 2015

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

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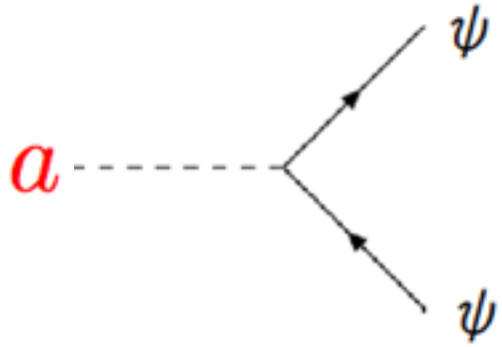
general effective couplings

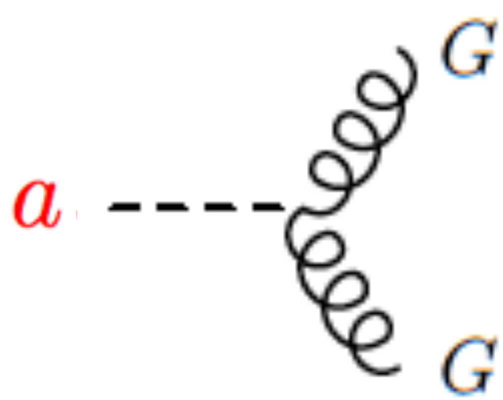
THEORY plus NEW SIGNALS at colliders

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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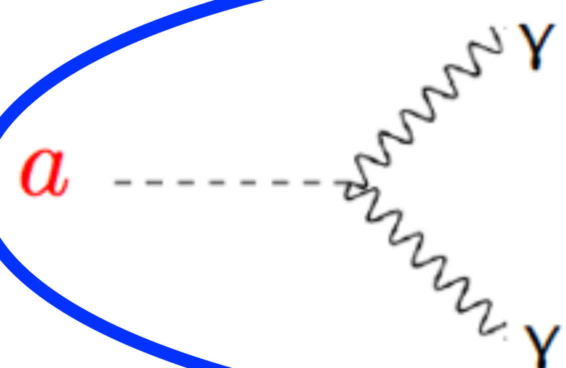
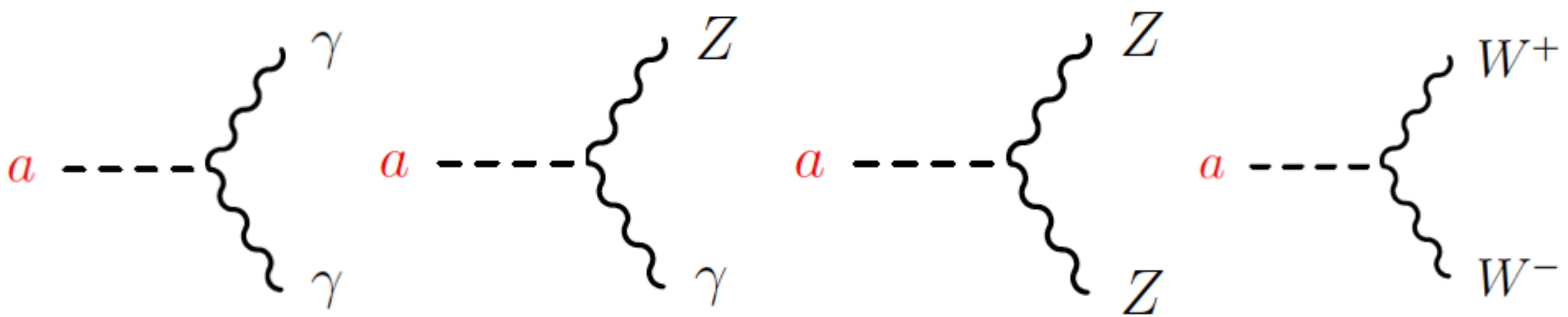


$$a\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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

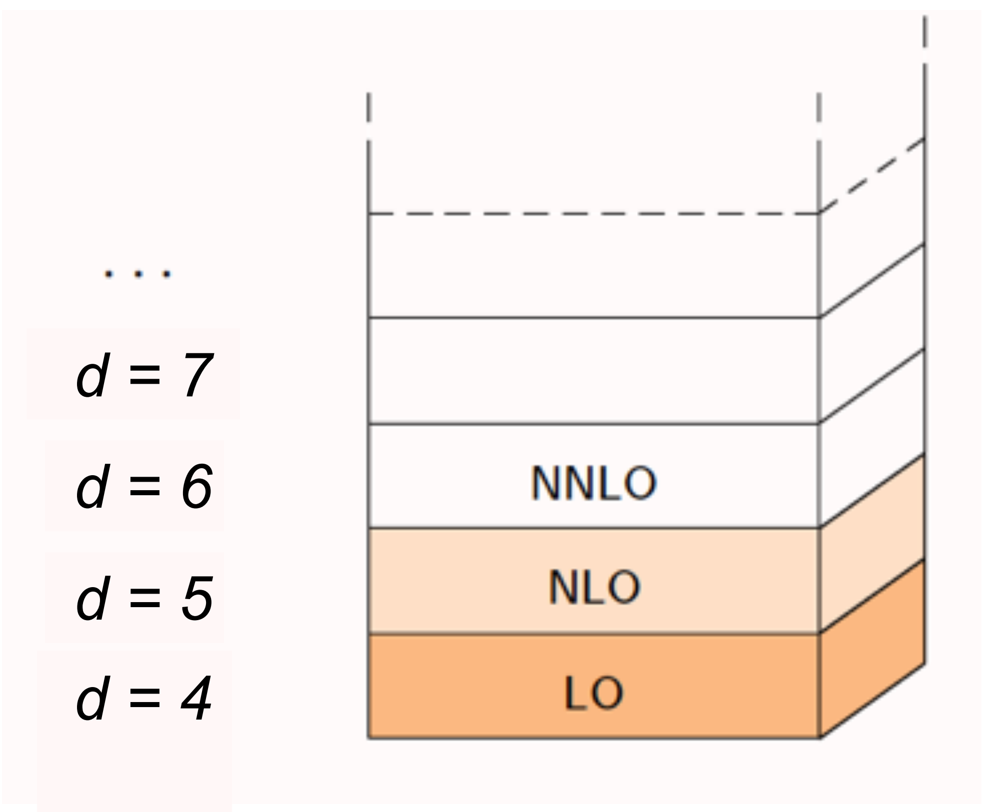
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_{i,n} c_{i,n}\, \mathbf{O}_i^{d=n}$$

Linear = SM EFT —> Physical **h** and Goldstone bosons π^a together in the Φ $SU(2)_L$ doublet

$$\Phi = \begin{pmatrix} \pi^1 + i\pi^2 \\ v + h + \pi^3 \end{pmatrix} \approx (v + \mathbf{h})\, e^{i\pi^a\sigma^a/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = (v + \mathbf{h})\, \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Expansion in canonical dimensions Φ/f_a , D_μ/f_a:

tower of $\mathbf{O}_i^{d=n}$ with mass dimension n



ALP-Linear effective Lagrangian at NLO

II
SM EFT

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

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

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

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Georgi, Kaplan, Randall 1986

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SM higgs doublet

Georgi, Kaplan, Randall 1986

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

Georgi, Kaplan, Randall 1986

ALP-Linear effective Lagrangian at NLO

II

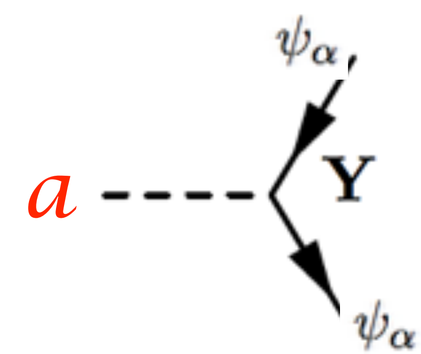
SM EFT

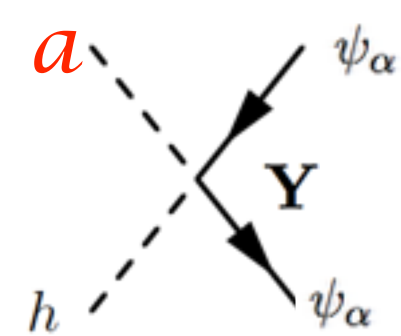
If only **bosonic** ALP-operators are considered:

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

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

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{a\Phi} = i\frac{a}{f_a}\sum_{\psi=Q,L}\left(\bar{\psi}_L \mathbf{Y}_\psi \mathbf{\Phi}\sigma_3\psi_R\right) + \text{h.c.}$$





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

||
SM EFT

Complete basis (bosons+fermions):

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

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

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

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):

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

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

$$\bar{\psi}\gamma_\mu X_\psi \psi \quad \psi = Q_L, Q_R, L_L, L_R \qquad f_a$$

where X_ψ is a general 3x3 matrix in flavour space

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

e: NO a-Higgs bosonic couplings

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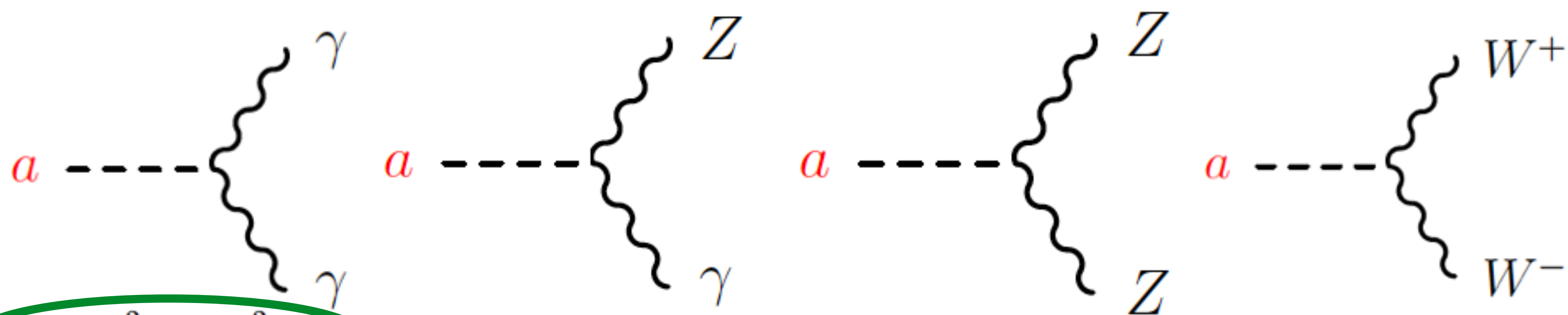
where X_ψ is a general 3x3 matrix in flavour space

contain a-γγ and other couplings

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

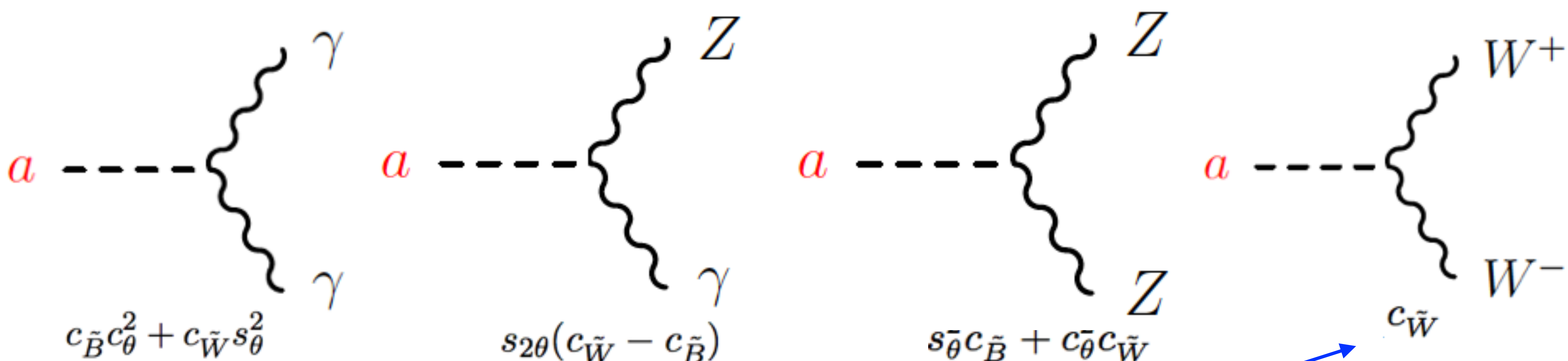


$c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2$

_a_-γγ studies only bounds this combination of couplings

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

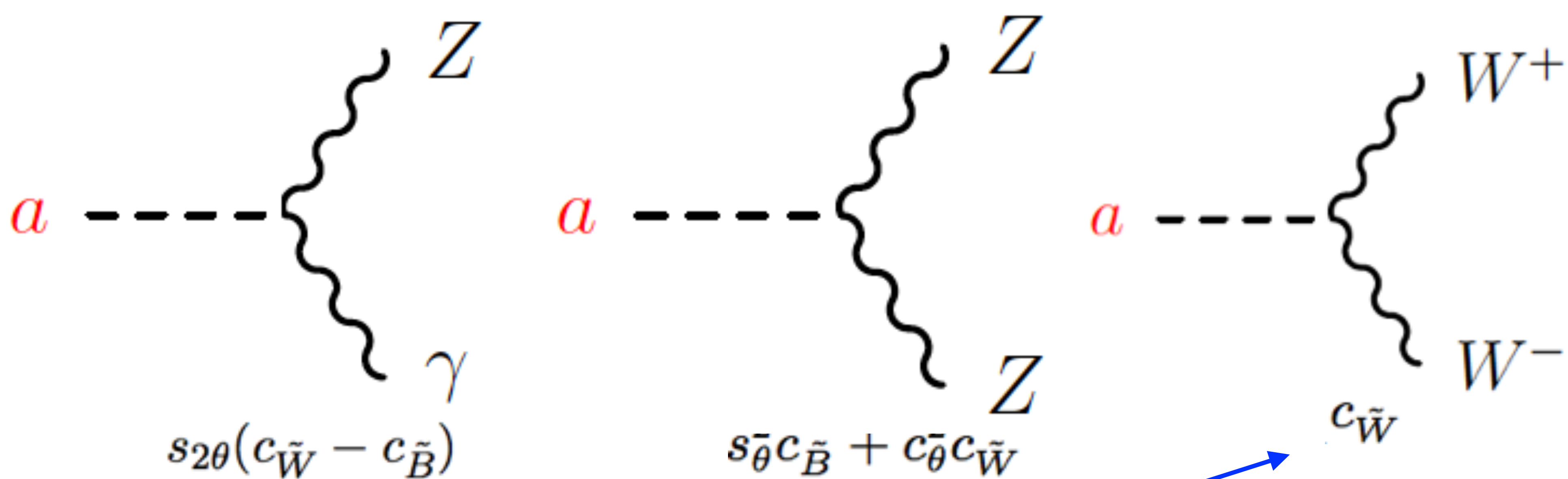
Because of SU(2)xU(1) gauge invariance, a-γγ comes together with a-γZ, a-ZZ and a-W⁺W⁻ :



Largely disregarded up to very very recently

only a tiny bit in Jaeckel+Spannowsky 2015

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



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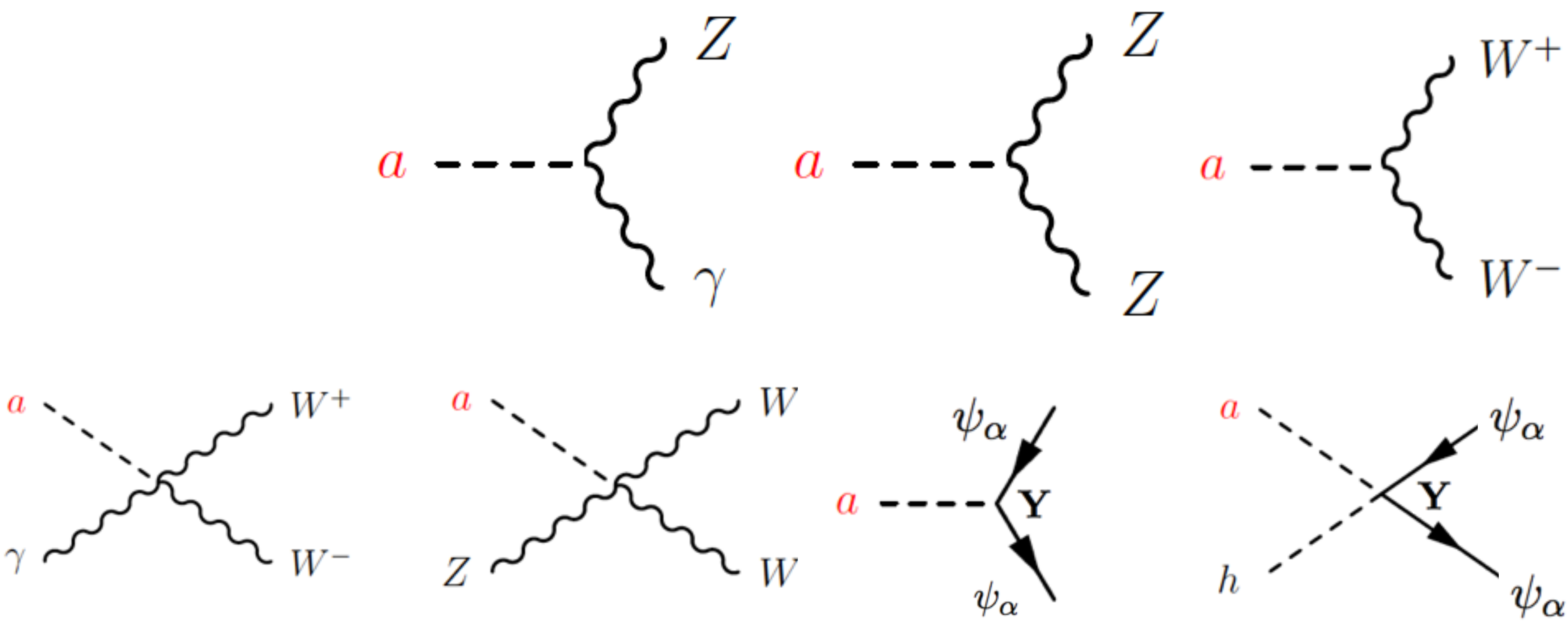
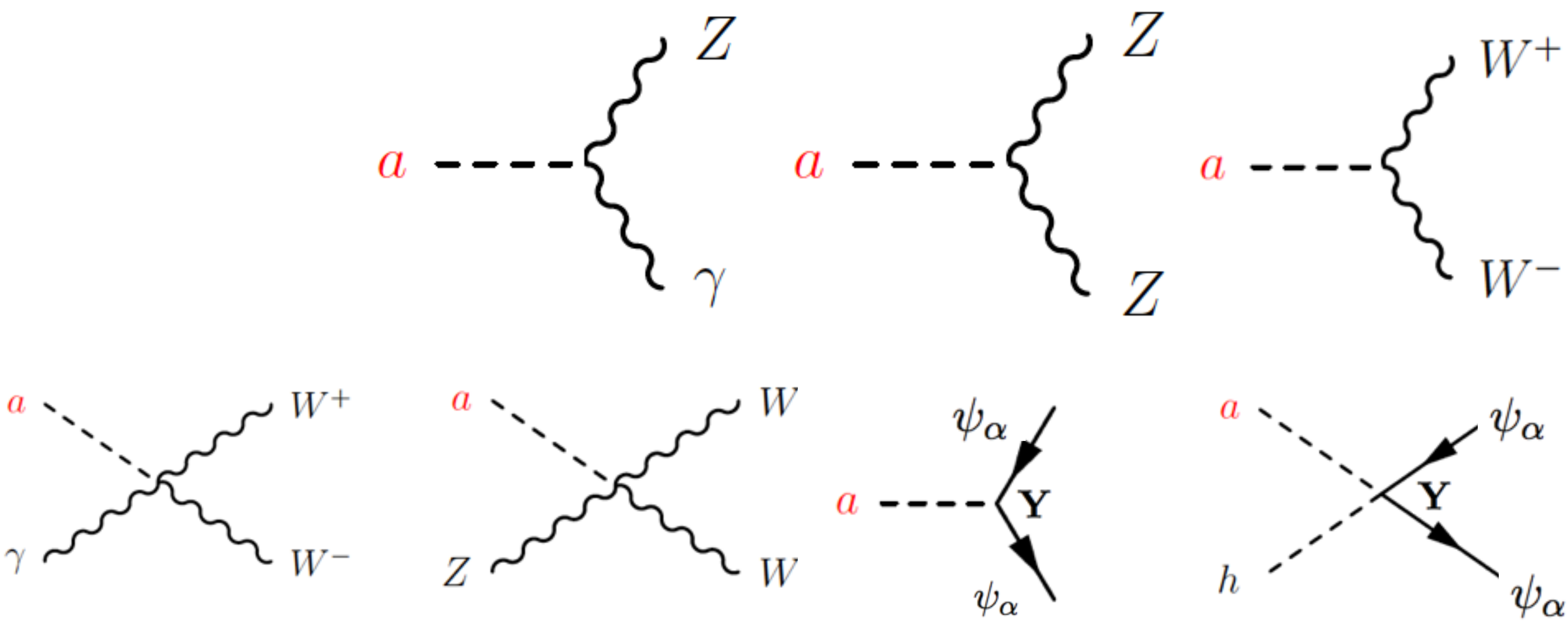


We analyzed the impact at LEP, LHC and HL-LHC of bosonic effective *a*-SM couplings:

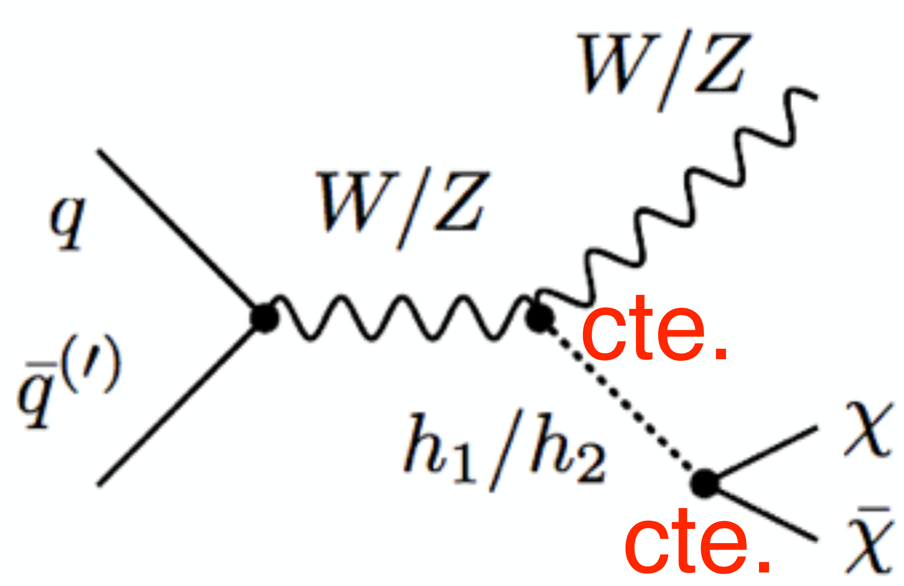
→ New signals: mono-Z, mono-W, associated *a*Wγ, *a*t$\bar{t}$

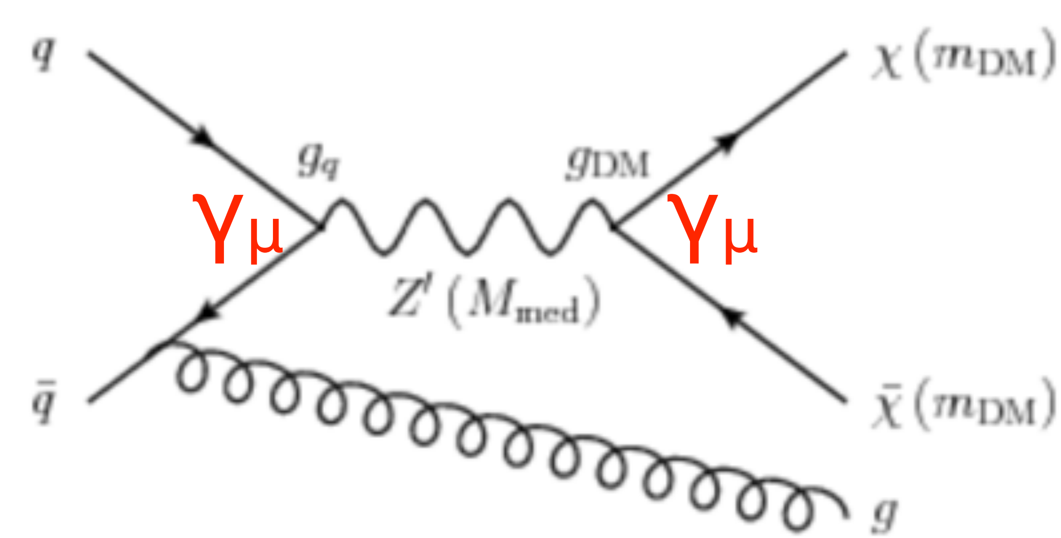


A general, largely unexplored, ALP characteristic:
all couplings are derivative = grow with 4-momentum

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

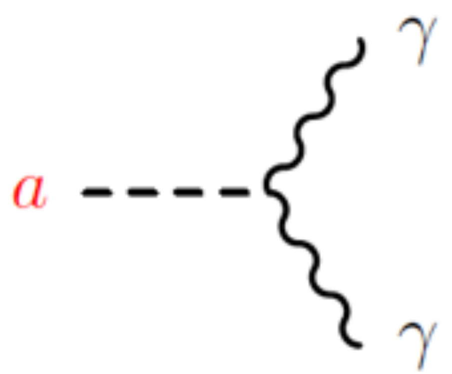
for instance Z' or DM searches typically assume vectorial or scalar couplings:



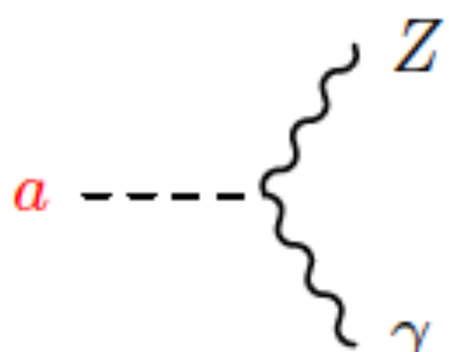


A general, largely unexplored, ALP characteristic: all couplings are derivative = grow with 4-momentum

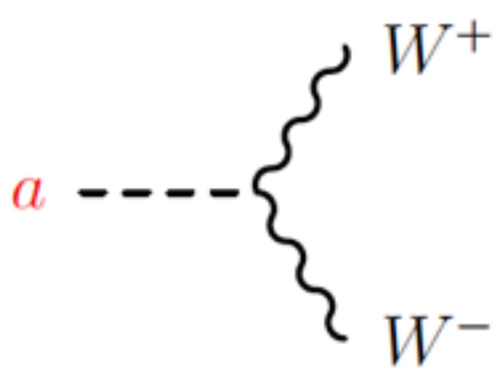
e.g.



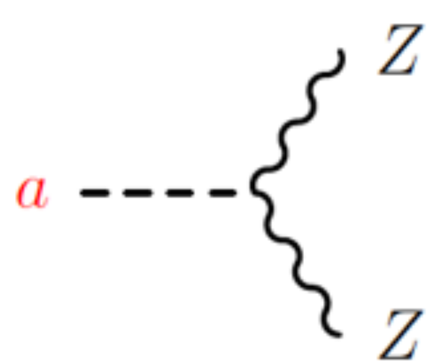
$$-\frac{4i}{f_a} p_{A1\alpha} p_{A2\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_\theta^2 c_{\tilde{B}} + s_\theta^2 c_{\tilde{W}}\right)$$



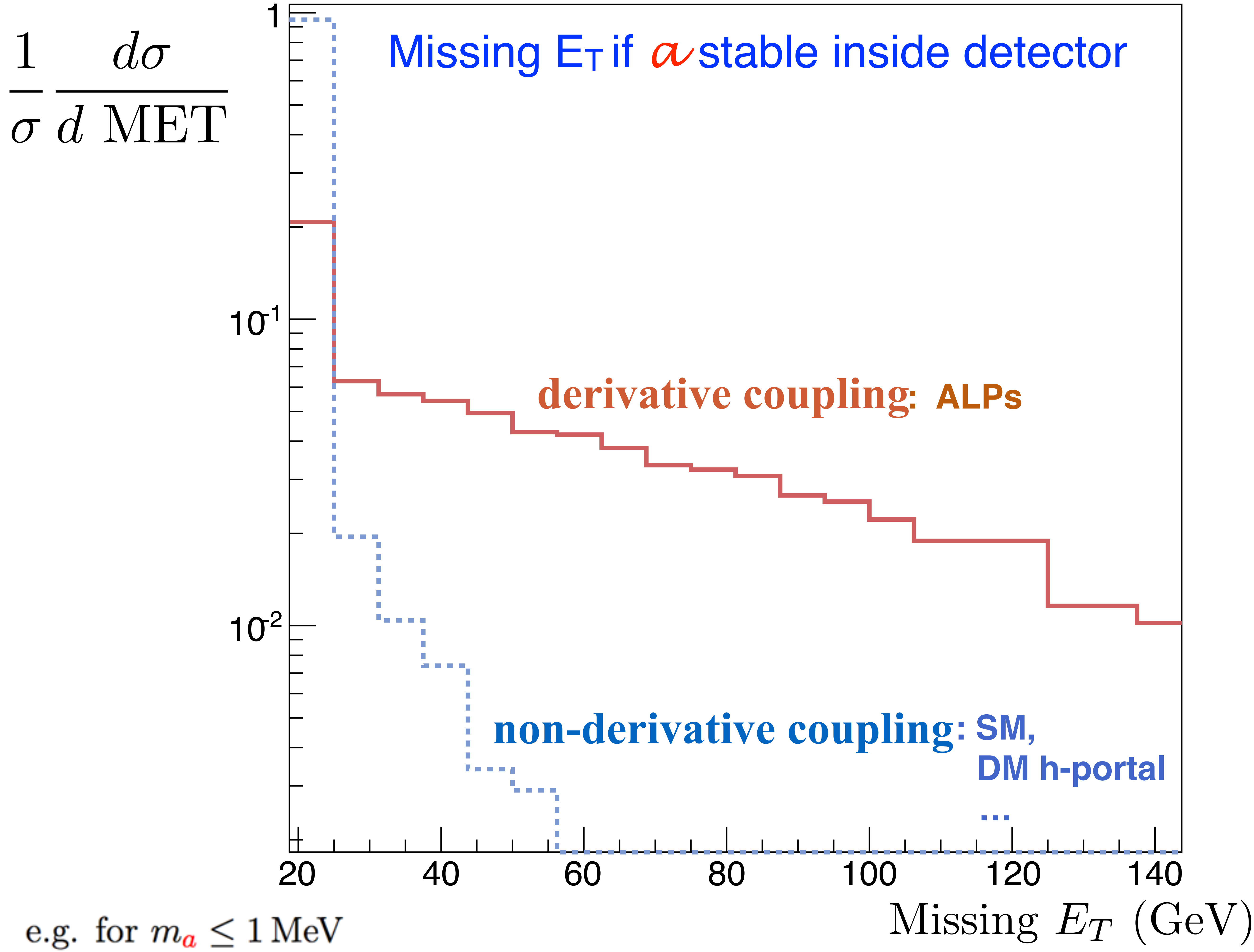
$$\frac{2is_{2\theta}}{f_a} p_{Z\alpha} p_{A\beta} \varepsilon^{\mu\nu\alpha\beta} \left(c_{\tilde{B}} - c_{\tilde{W}}\right)$$



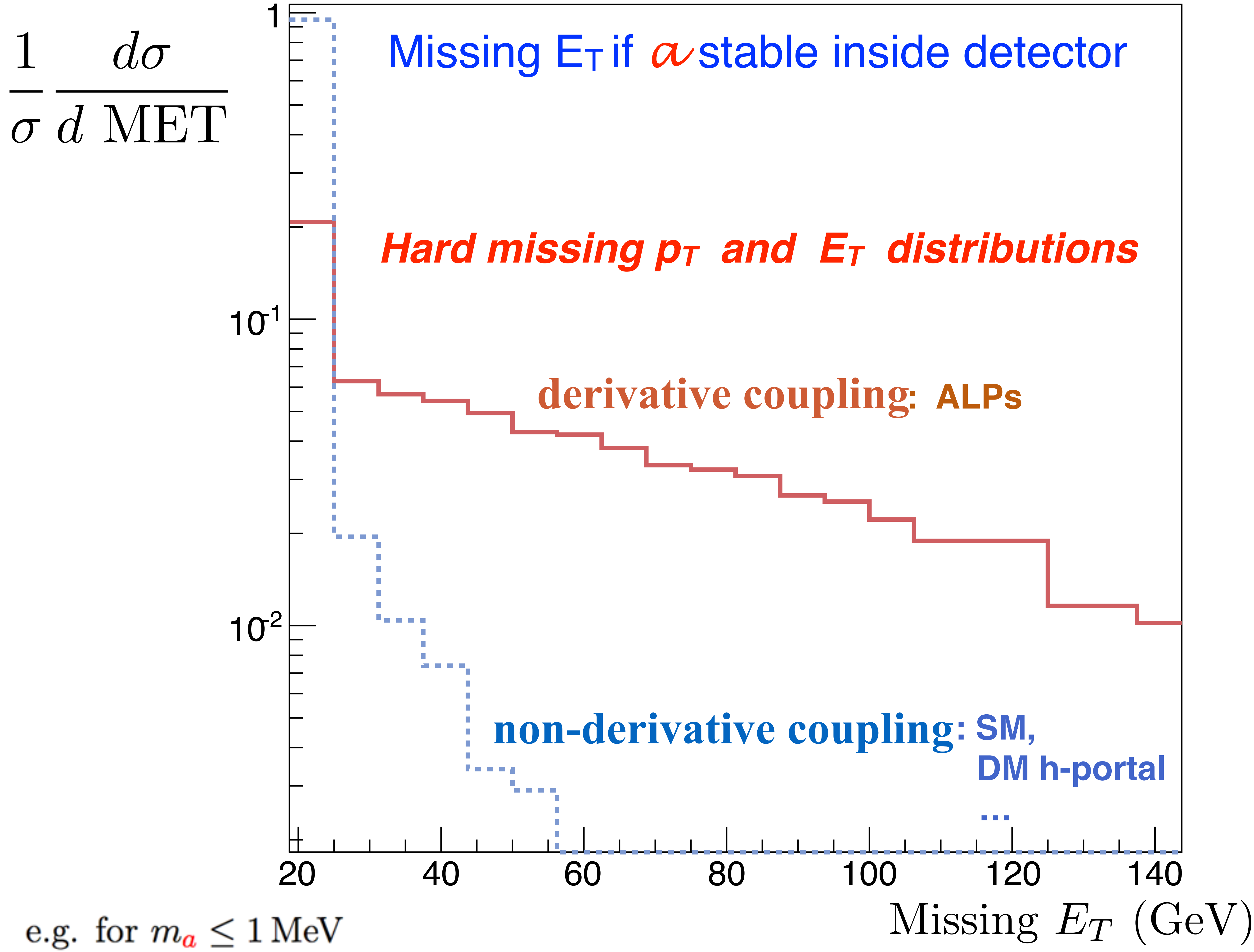
$$-\frac{4i}{f_a} c_{\tilde{W}} p_{+\alpha} p_{-\beta} \varepsilon^{\mu\nu\alpha\beta}$$



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

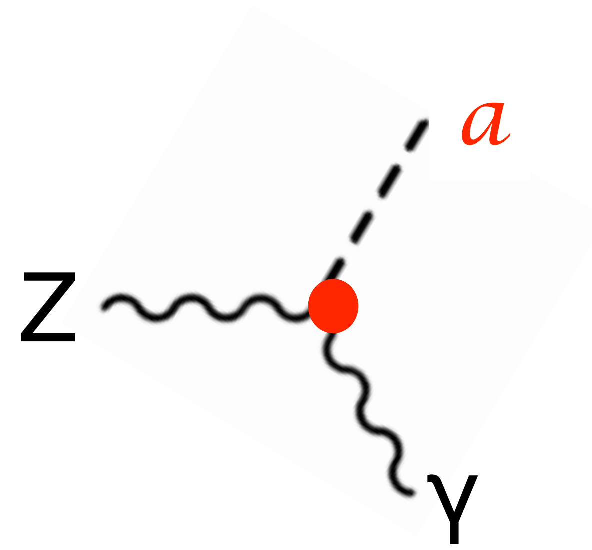


$\frac{1}{\sigma}\frac{d\sigma}{d\ \mathrm{MET}}$
Missing E_T if a stable inside detector
derivative coupling: ALPs
non-derivative coupling: SM,
DM h-portal
...
1
10^{-1}
10^{-2}
20
40
60
80
100
120
140
Missing E_T (GeV)
e.g. for $m_a \leq 1\,\mathrm{MeV}$

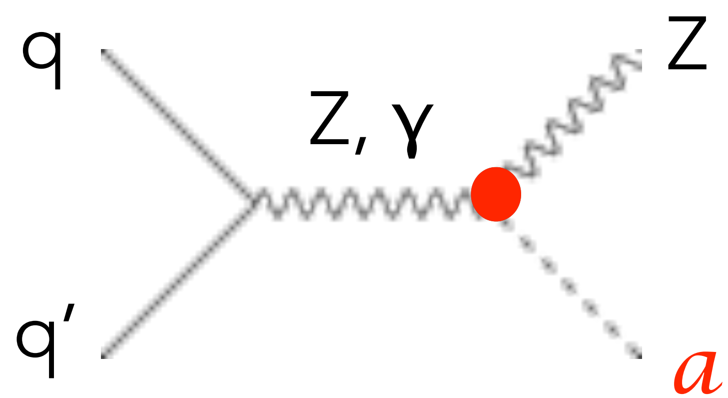


$\frac{1}{\sigma}\frac{d\sigma}{d\ \mathrm{MET}}$
Missing E_T if a stable inside detector
Hard missing p_T and E_T distributions
derivative coupling: ALPs
non-derivative coupling: SM,
DM h-portal
...
1
10^{-1}
10^{-2}
20
40
60
80
100
120
140
Missing E_T (GeV)
e.g. for $m_a \leq 1\,\mathrm{MeV}$

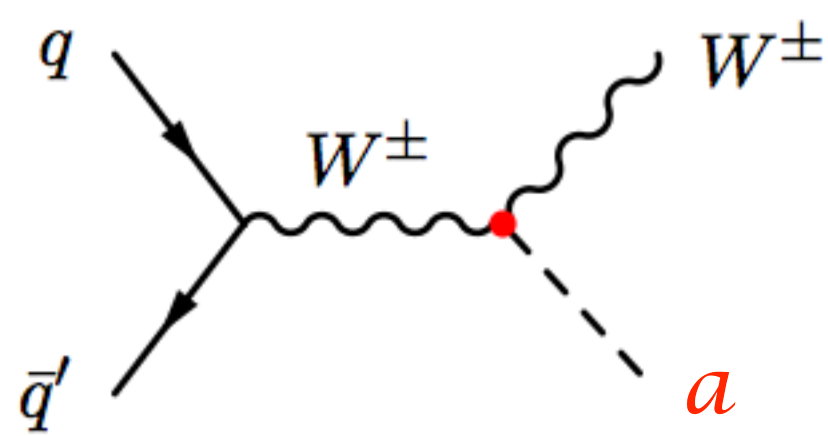
We explored:



* LEP signals



* Mono-Z signals

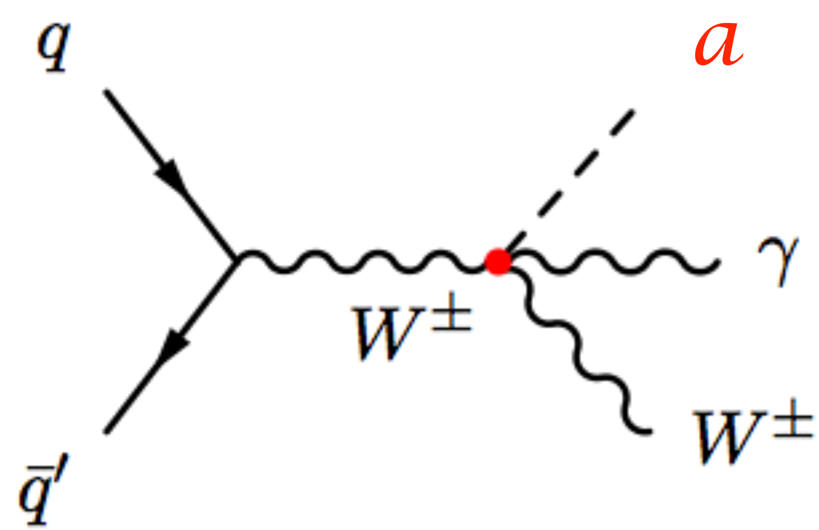


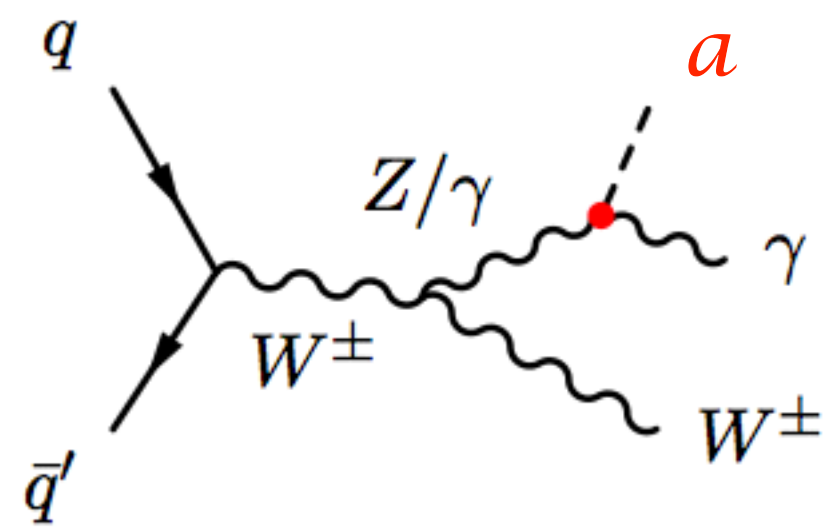
* Mono-W signals

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

Rocio del Rey's talk this afternoon

* Associated ALP-γ-W

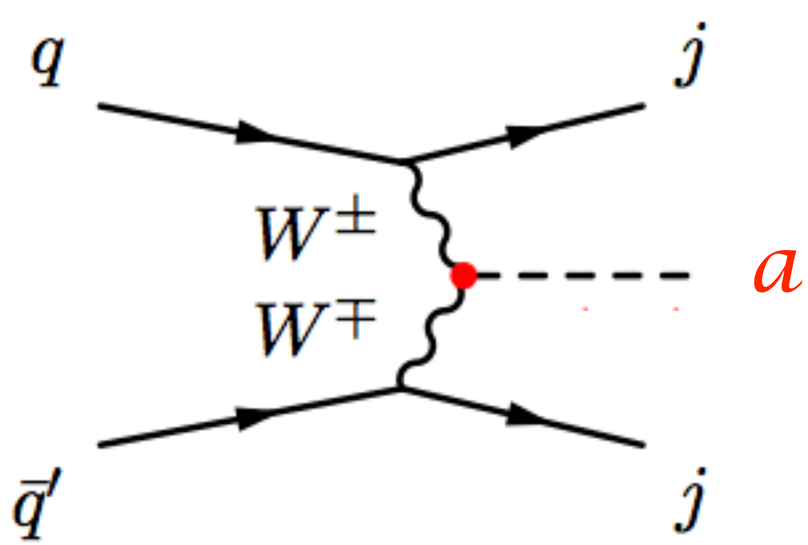


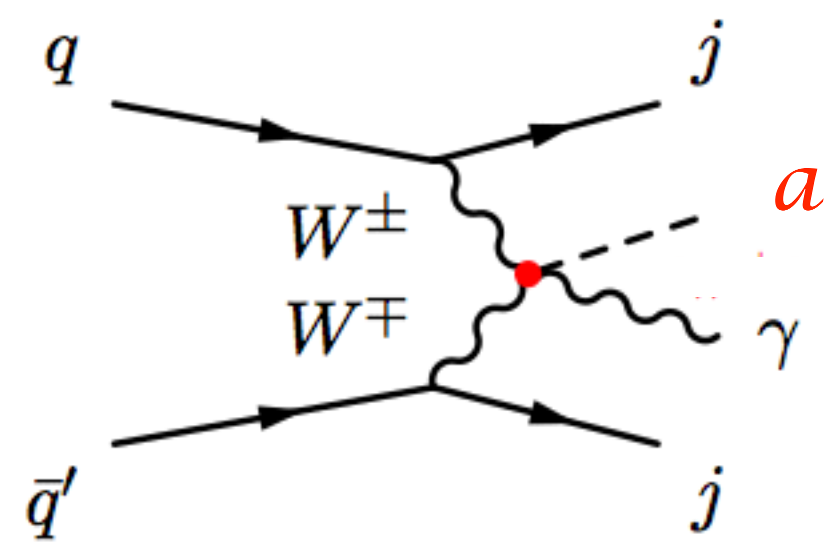


this channel not yet analysed by ATLAS and CMS

Promising at HL-LHC

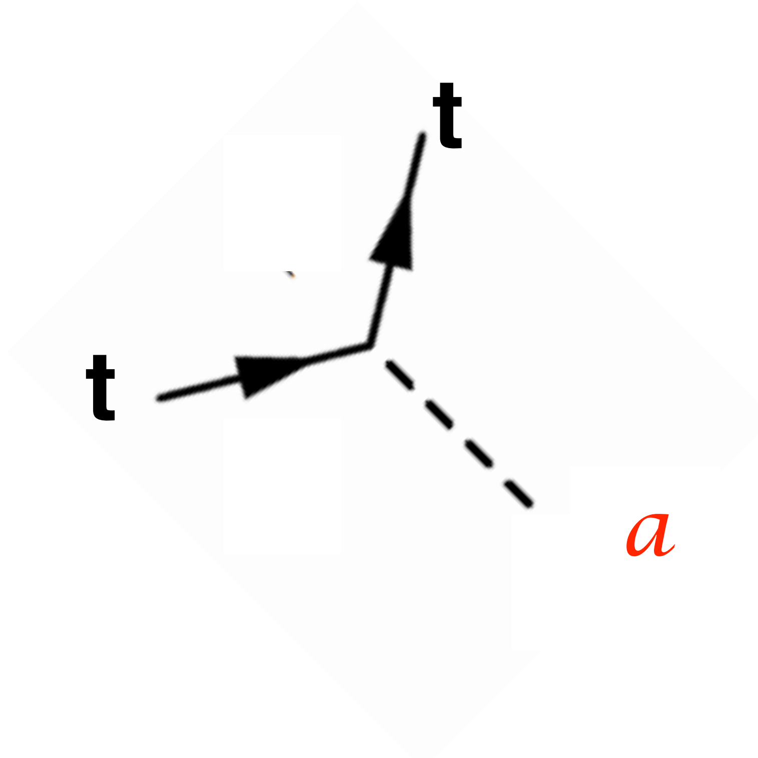
* Others:





Rocio del Rey's talk this afternoon

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



→ **Rocio del Rey's talk this afternoon**

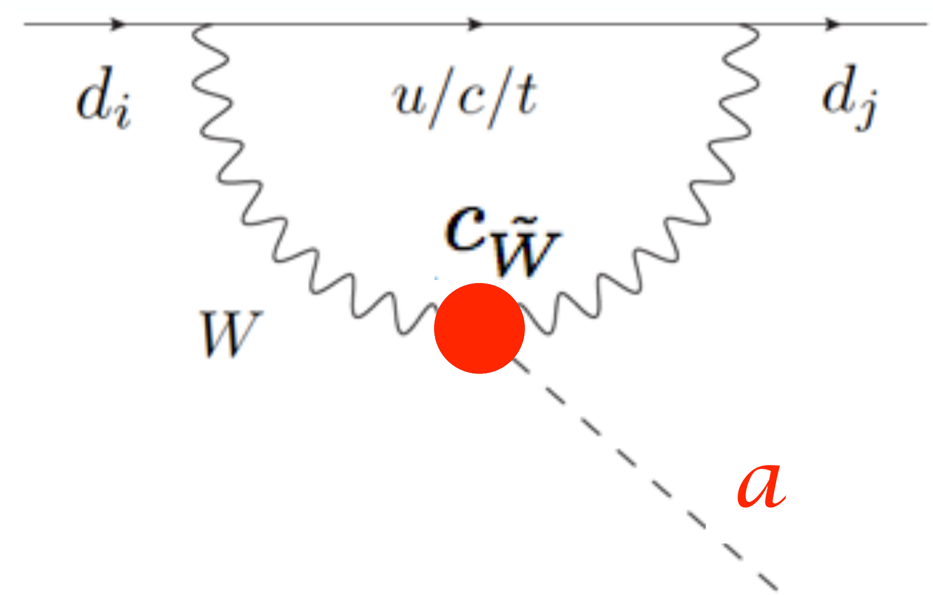
We bound or showed a reach on $\frac{f_a}{c_i}$ within 0.5 - 16 TeV

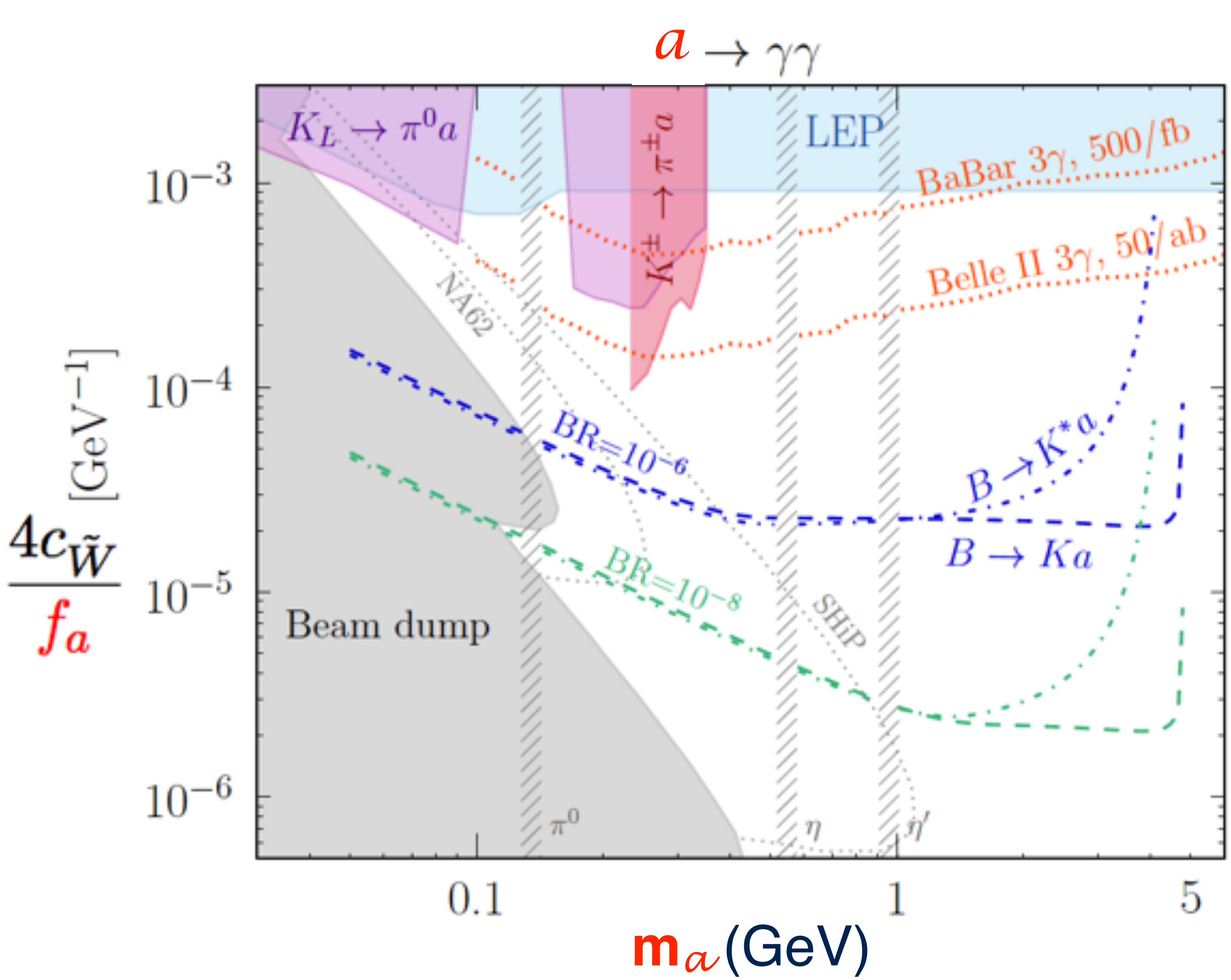
for $m_a <$ MeV or simply not decaying in the detector

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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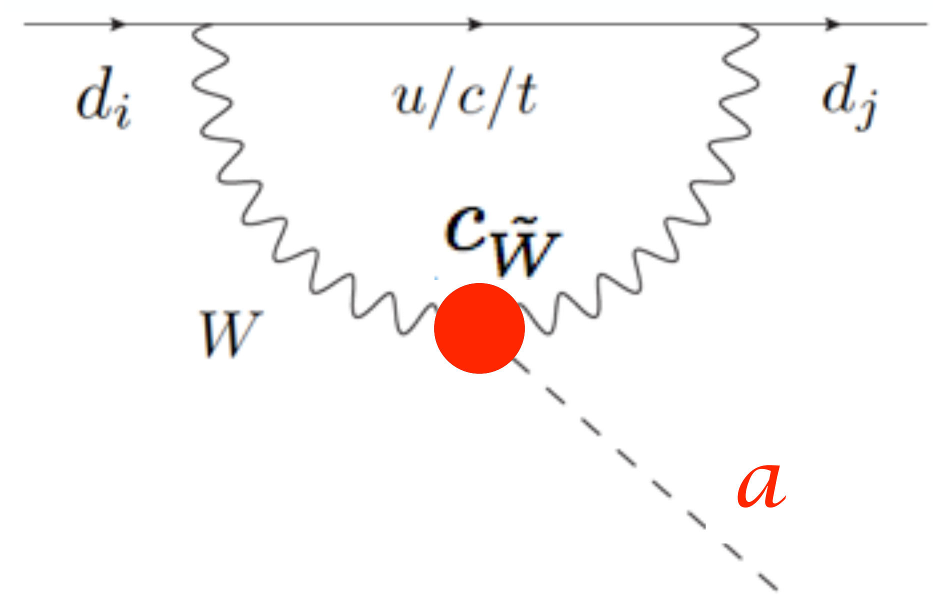
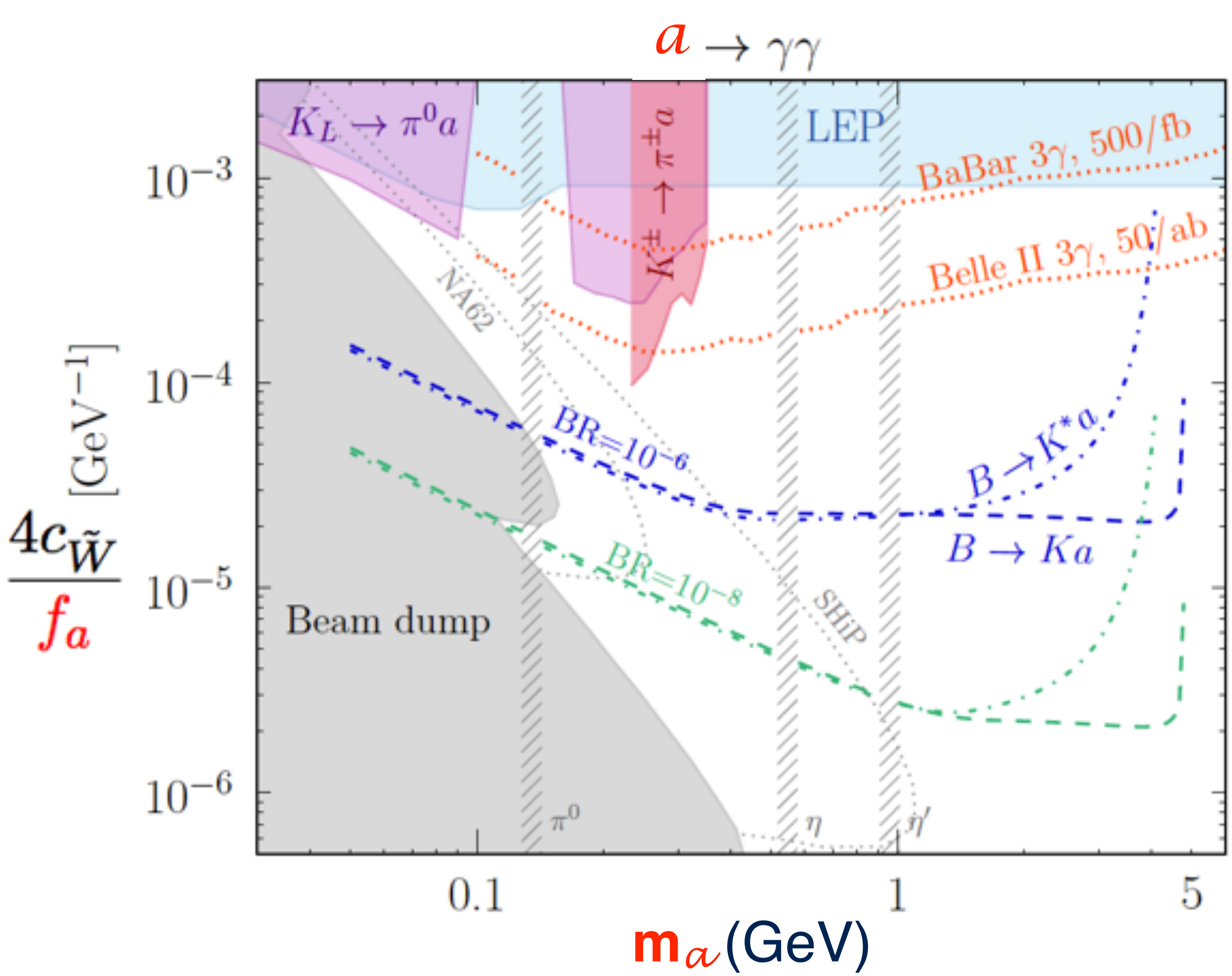
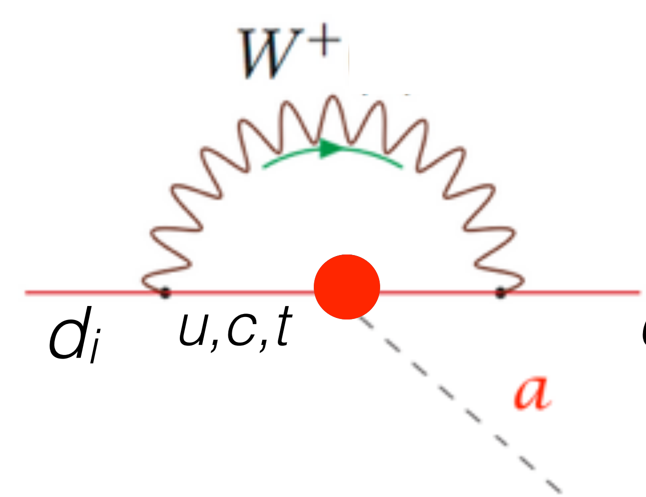




Izaguirre+Lin+Shuve 2016

But several ops. may contribute:

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



+Del Rey et al. in preparation

	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**

||
SM EFT

Higgs field: $\Phi = (v + \mathbf{h})\ \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$; $\mathbf{U} = e^{i\pi^a \sigma^a / v}$

Longitudinal W,Z

It assumes that **h** is in an exact $SU(2)_L$ doublet

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

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

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

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: $\Phi = (\cancel{v + \mathbf{h}})\, \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$; $\mathbf{U} = e^{i\pi^a\sigma^a/v}$

Longitudinal W,Z

independent !

some couplings decorrelate:
more operators at given order

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

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

Higgs EFTs

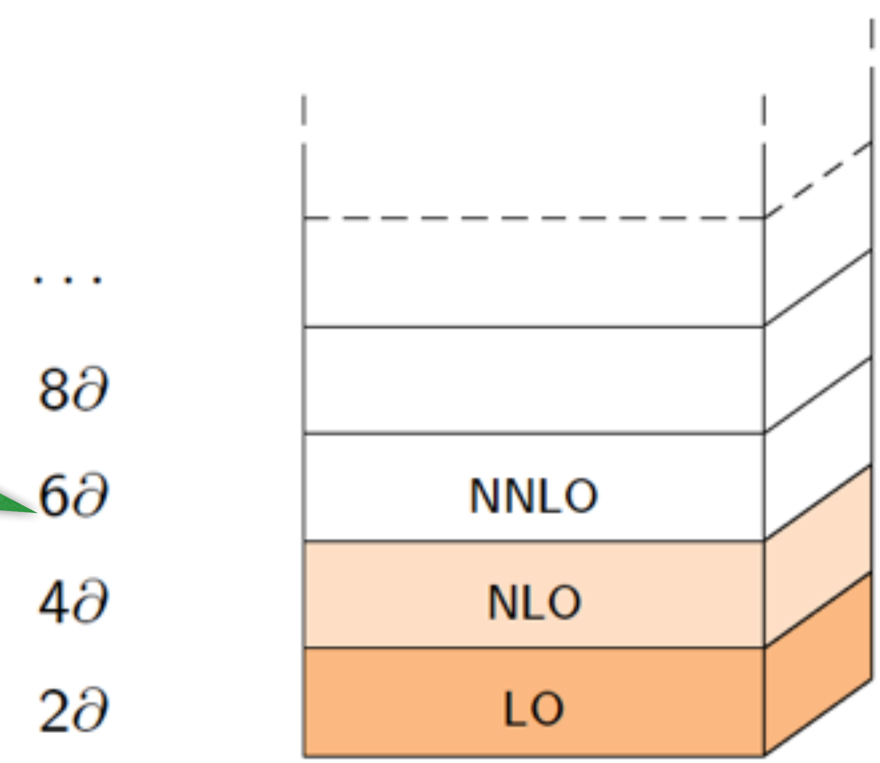
Linear or **Chiral** (non-linear)

in chiral: $\phi \to F(h)\, U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Godstone bosons = $e^{i\pi^a\sigma^a/v}$

U adimensional

Expansion in derivatives: D_μ/Λ :



In EFT, the weight of **h** is arbitrary
we use **h**/v, but the conclusions
would be the same with **h**/f

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

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

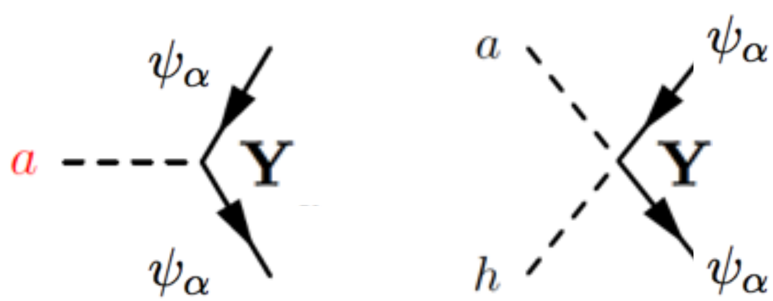
Higgs EFTs

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

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

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



as in the linear case

Higgs EFTs

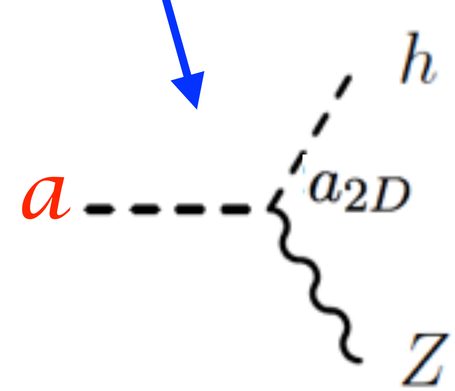
Linear or **Chiral** (non-linear)

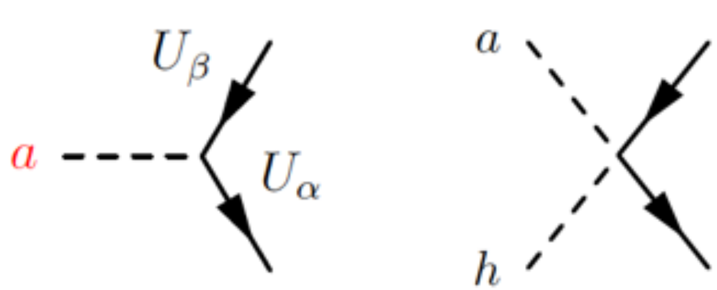
LO: $\mathscr{L}_a^{\rm LO} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h)$ where $\mathcal{A}_{2D}(h) = iv^2\,\frac{\partial^\mu a}{f_a}\,{\rm Tr}[\mathbf{T}\mathbf{V}_\mu]\,\mathcal{F}_{2D}(h)$

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

ALP-Higgs couplings survive !!

(unlike linear case)





as in the linear case

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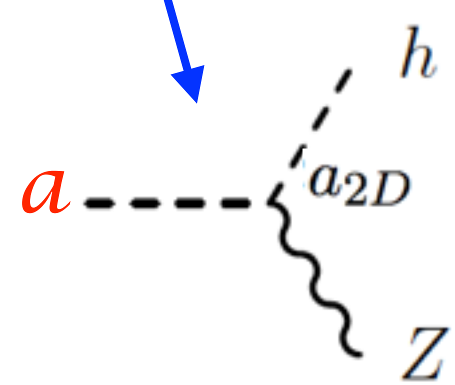

while in the linear expansion such couplings would appear only at NNLO

(Bauer, Neubert, Tham 2016)

Higgs EFTs

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

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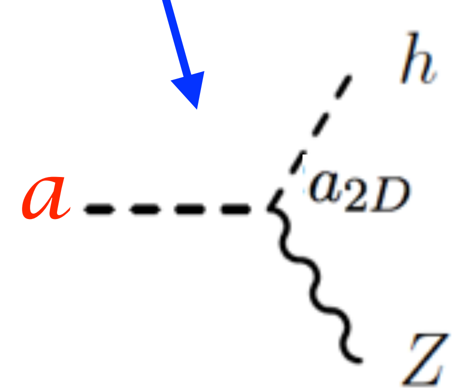
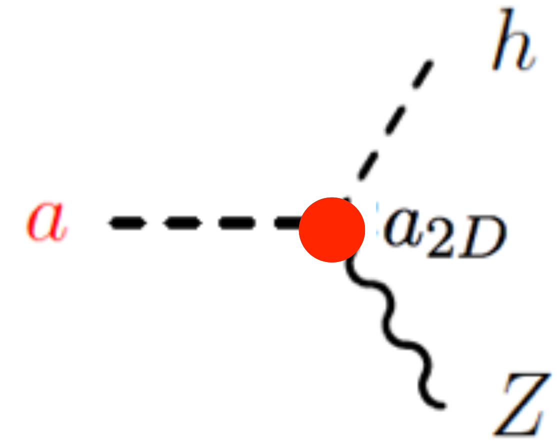


New additional signals: mono-h, BSM Higgs decays

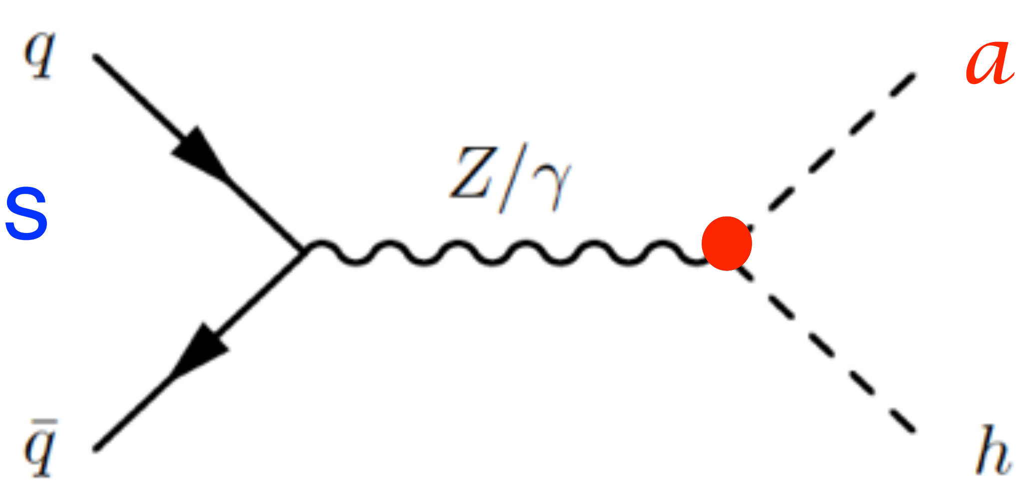
We explored LO chiral signals:

* Non-standard Higgs decays



BR(h—>BSM) more constraining than Γ_h—> inv.

* Mono-Higgs signals



di-Higgs etc.

Rocio del Rey's talk this afternoon

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 $\mathcal{A}_{2D}(h) = iv^2\frac{\partial^\mu a}{f_a}{\rm Tr}[\mathbf{T}\mathbf{V}_\mu]\mathcal{F}_{2D}(h)$

NLO, bosonic custodial preserving:

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

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

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

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

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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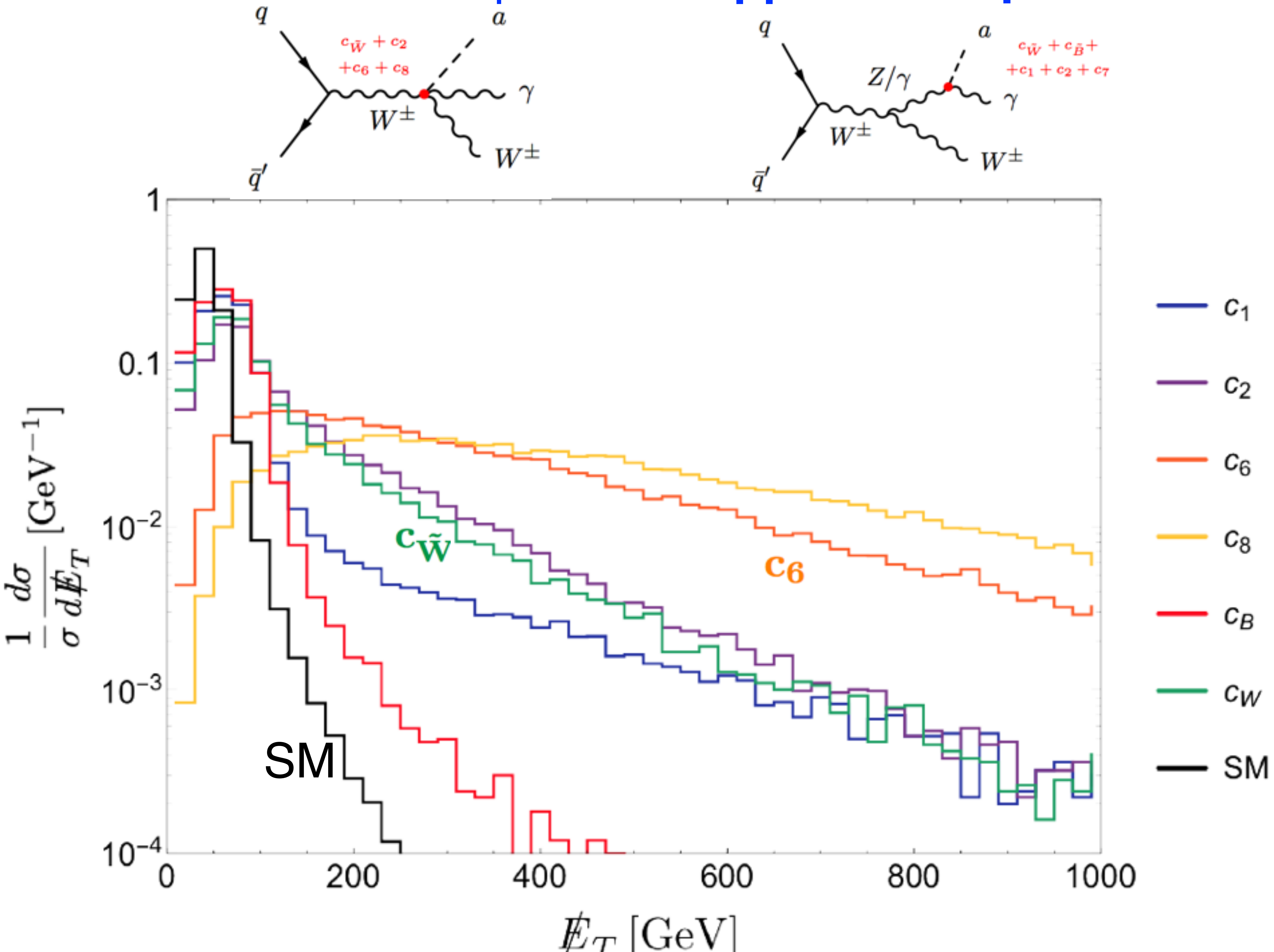
We also determined the complete basis of non-redundant bosonic +fermionic couplings at NLO

Associated production pp —> aWγ

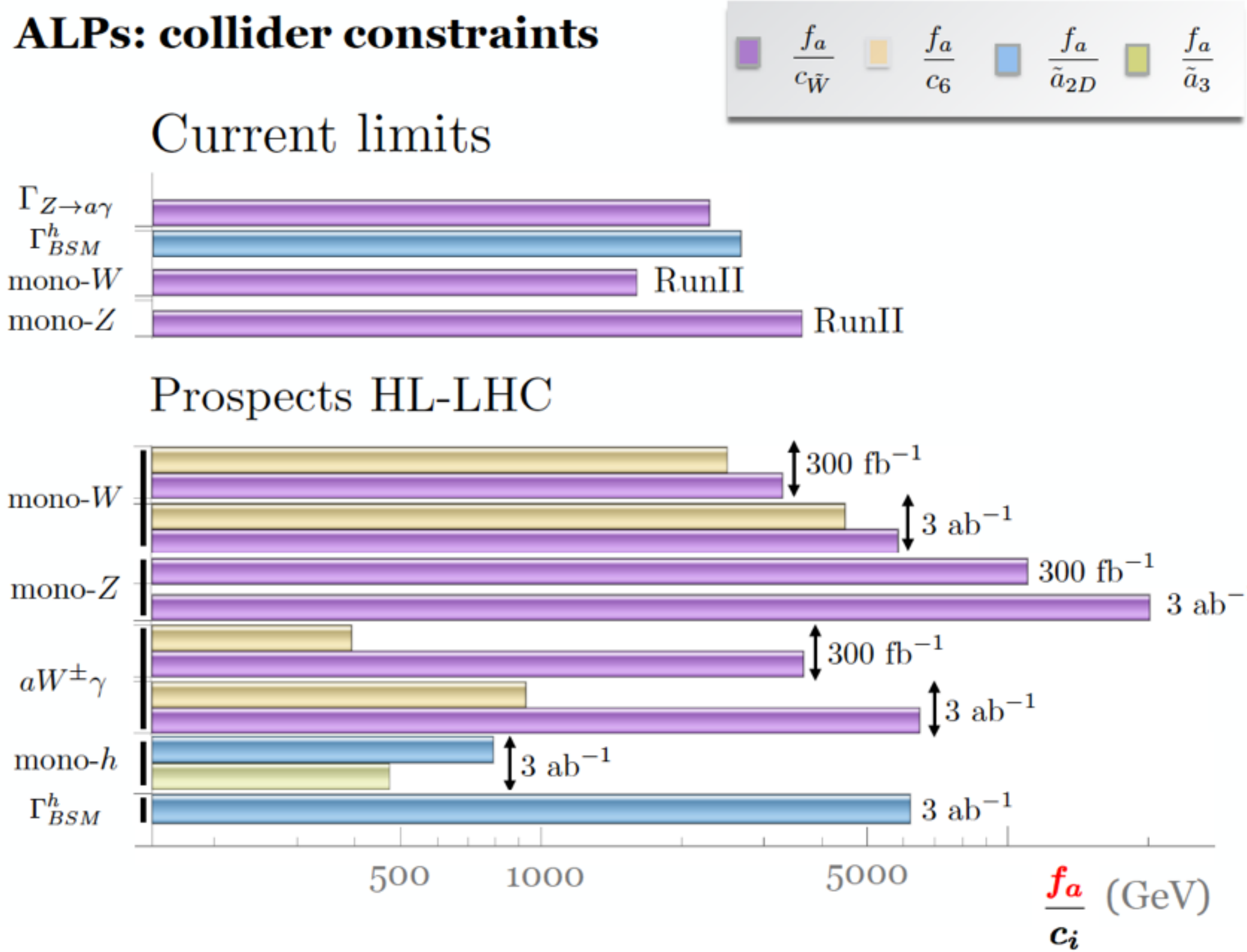


	Observables/Processes		
			Linear
	Astrophysical obs.	$g_{a\gamma\gamma}$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$
	Rare meson decays		$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{a\Phi}}$
New constraints	**LEP data**		
	BSM Z width	$\Gamma(Z \to a\gamma)$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$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

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

Rocio del Rey’s talk this afternoon

ALPs: collider constraints



95%CL

LHC 13 TeV
2σ reach

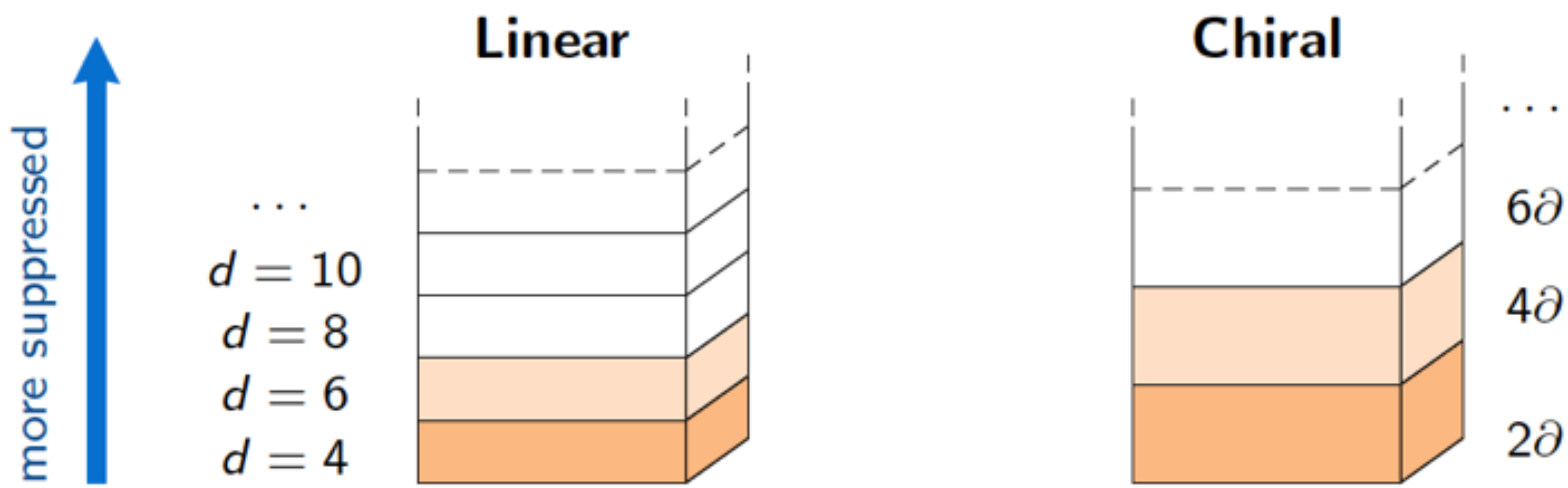
flattish MET are ALP signals

Higgs EFTs

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

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.



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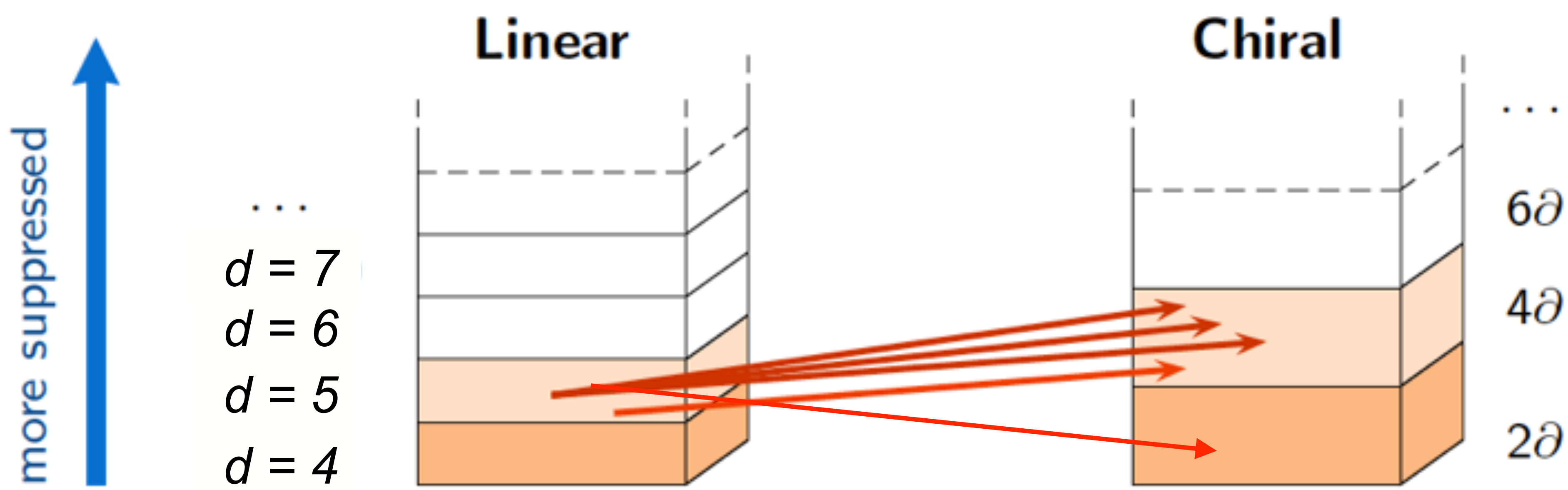

correlations:

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

decorrelations:

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

Higgs EFTs

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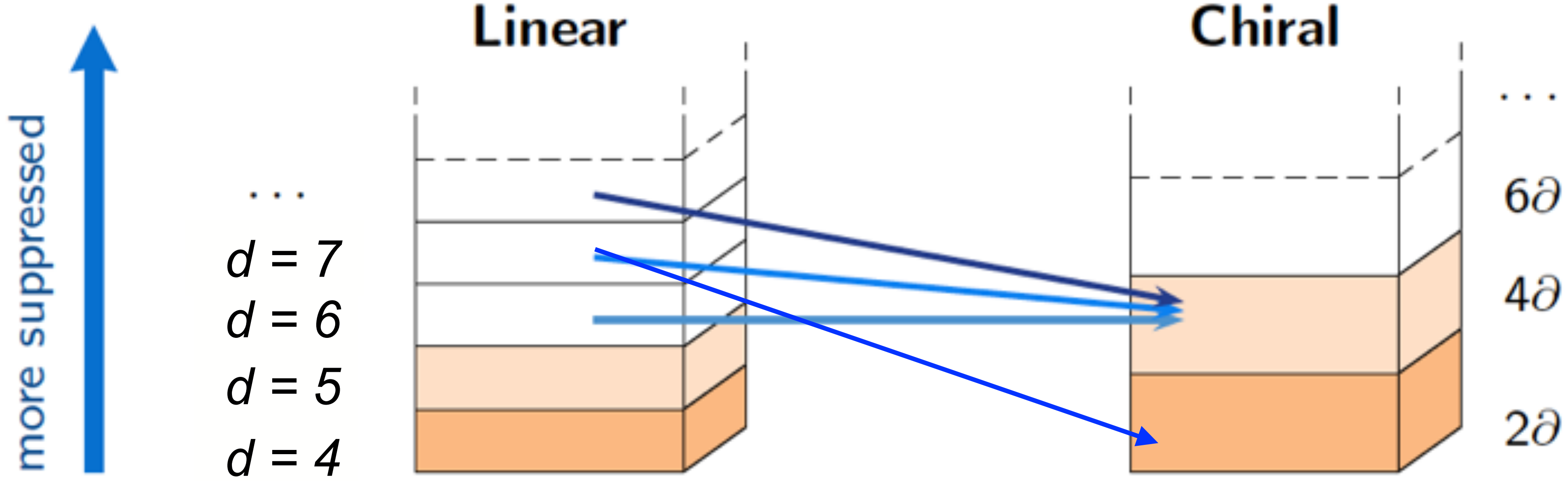


Connected to NLO $d = 5$ operators in the linear expansion

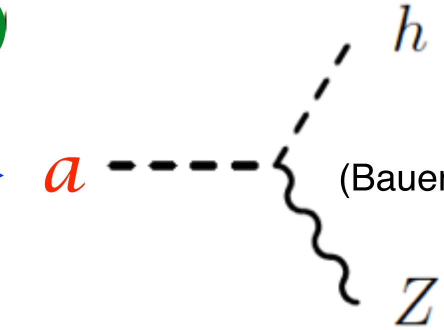
LO Chiral: Fermionic vertices induced by $\mathcal{A}_{2D} \longrightarrow \frac{-i}{2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)\frac{\partial_\mu a}{f_a}$

NLO Chiral

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

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

$$\mathcal{A}_7 \longrightarrow \frac{8i}{(4\pi)^2 v^4}(\Phi^\dagger \tilde{W}_{\mu\nu}\Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)\frac{\partial^\nu a}{f_a}$$

$$\mathcal{A}_{13} \longrightarrow -\frac{4i}{(4\pi)^2 v^4}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\Box[\Phi^\dagger \Phi]\frac{\partial^\mu a}{f_a}$$

$$\mathcal{A}_{14} \longrightarrow -\frac{4i}{(4\pi)^2 v^4}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\partial^\mu \partial^\nu[\Phi^\dagger \Phi]\frac{\partial_\nu a}{f_a}$$

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

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

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 at LO!**

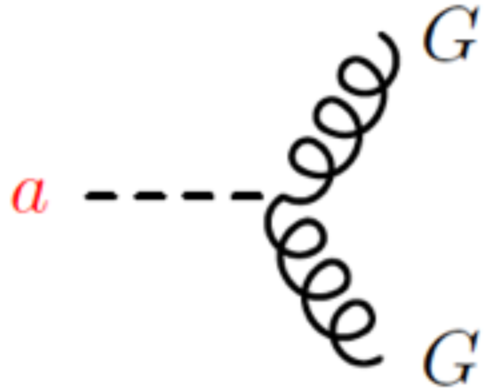
*** New ALP signals from linear(SMEFT) and non-linear Lags.**
MET —> mono-γ, -W/Z, -h, $\Gamma_{BSM}(h)$, etc. besides rare decays

Fish for them in your data!

*** All our results also apply to the CP-odd derivative couplings of a CP-even singlet scalar**

To do: many prompt and displaced signals (with high E_T/p_T dependence) if a decaying inside detector

Backup



Present bounds on gluon-ALP couplings

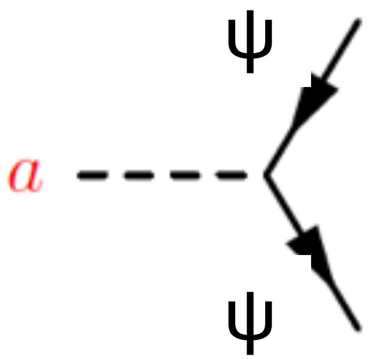
$$\mathcal{A}_{\tilde{G}} = -G^{a}_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

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)

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

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)

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

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.

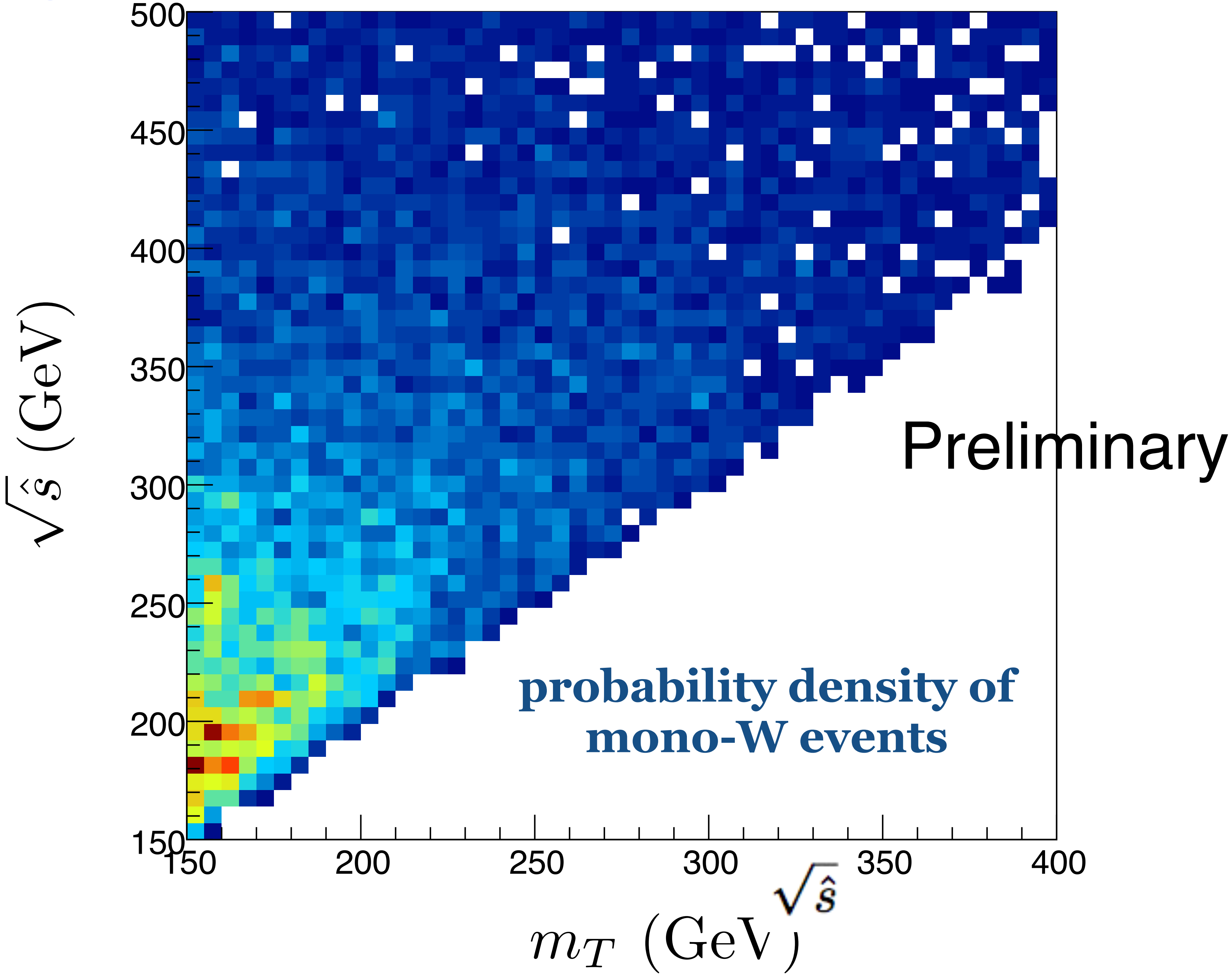
e.g. In mono-Z analysis with 2.3 fb^{-1}, the $\not{E}_T$ value for the highest bin considered is 1.2 TeV

That analysis valid for scales $f_a > 2.4$ TeV

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

For mono-W —> Correlation plot ————————->

Validity of the EFT, $m_T^{max} < f_a$ vs $\sqrt{\hat{s}} < f_a$



e.g. the difference between a cut in m_T^{max} and $\sqrt{\hat{s}}$ ^{max} at 350 GeV would be 16% of events; for 450% it would be 10% etc.

ALP stability at the LHC vs m$_a$

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

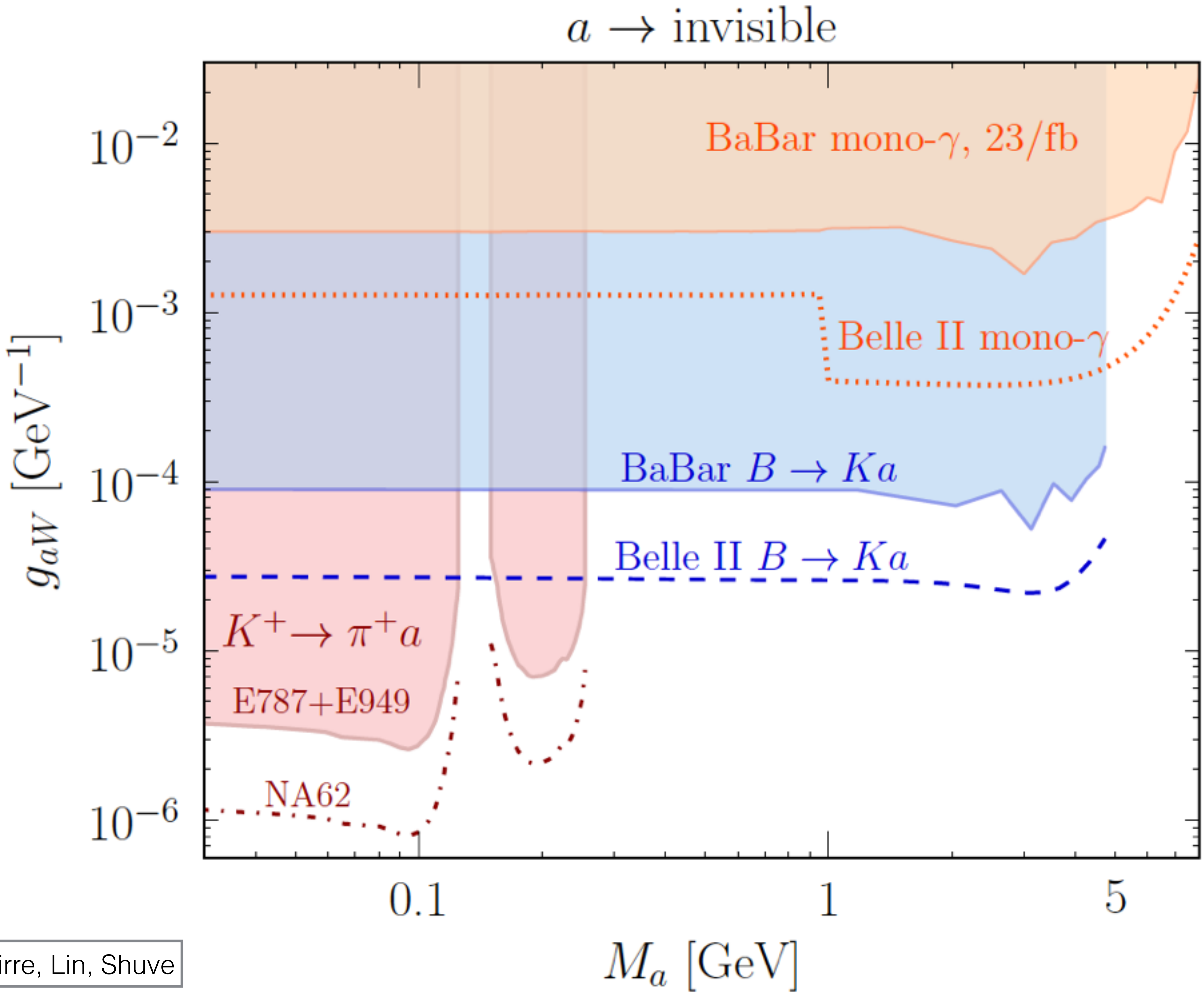
$\underline{a \to \nu\bar{\nu}\nu\bar{\nu}}$ It would simply become part of the $\not{E}_T$ contributions

$\underline{a \to \gamma\gamma}$ 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

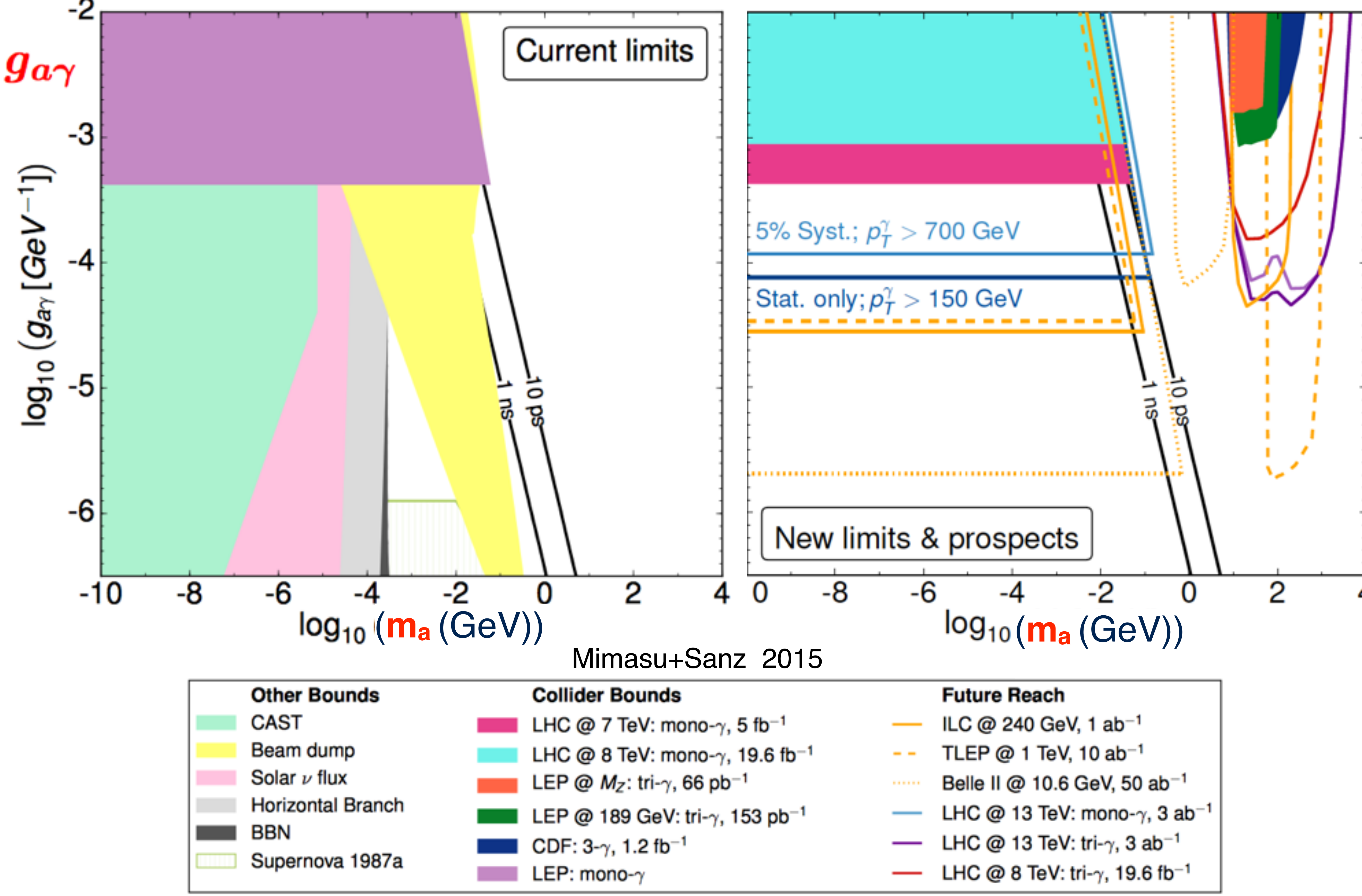
$$d \simeq 10^{22}\,\mathrm{m}\times\left(\frac{|\vec{p}_a|/g^2_{aZ\gamma}}{\mathrm{GeV}^3}\right) > 3.3\cdot 10^{27}\,\mathrm{m}\times\left(\frac{|\vec{p}_a|}{\mathrm{GeV}}\right)$$



Izaguirre, Lin, Shuve

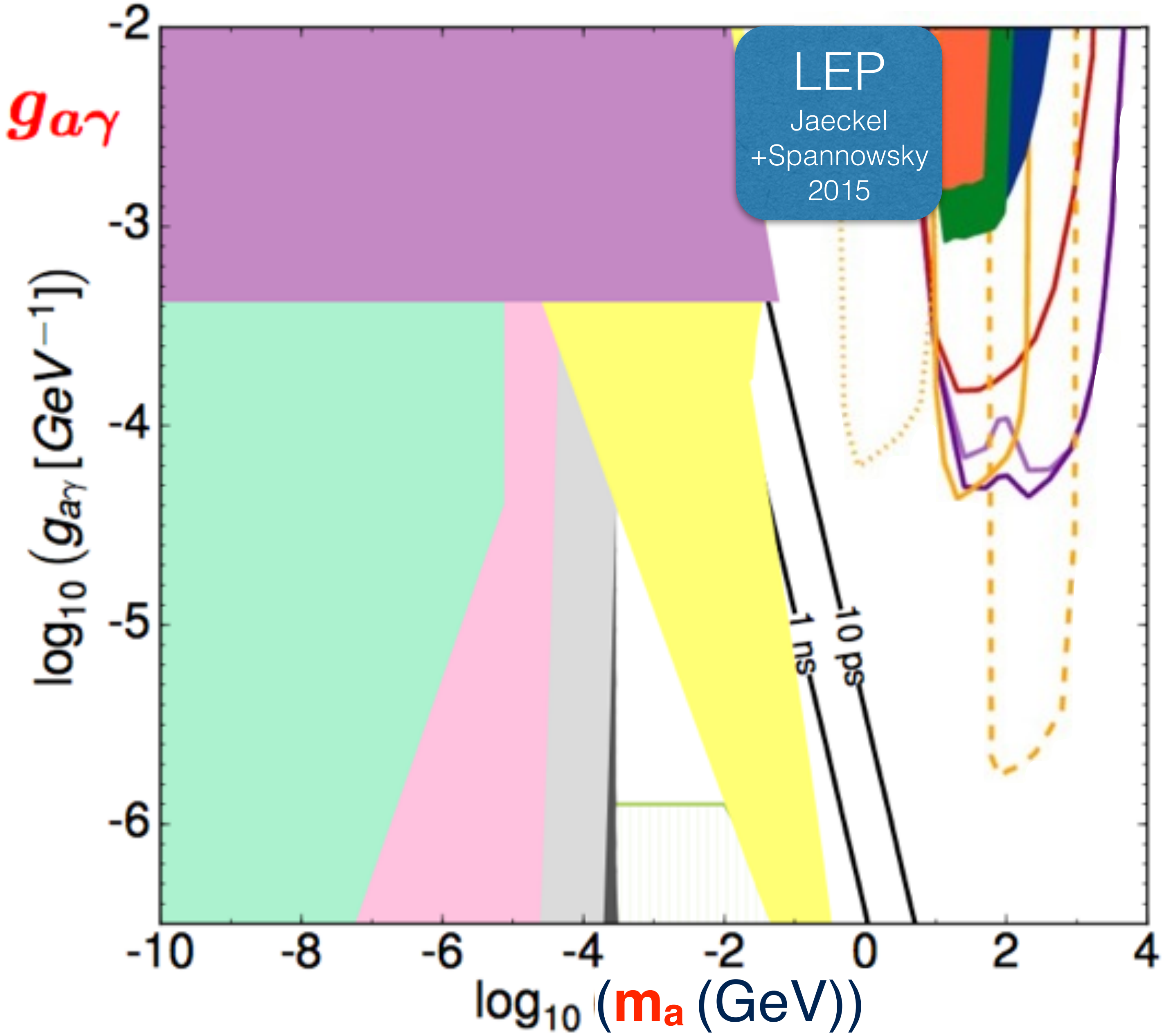
Bounds on photon-ALP coupling

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

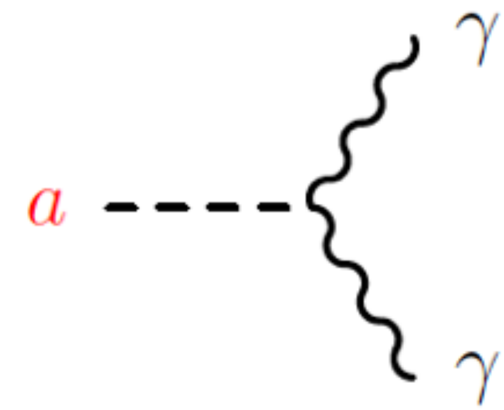


Mimasu+Sanz 2015

Present and future bounds on photon-ALP coupling



Mimasu+Sanz 2015



$$\delta\mathscr{L}_a^{\text{bosonic}} \supset -\frac{1}{4} g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

2016: further bounds from g-2 and dipole moments

Marciano+Masiero+Paradisi+Passera

Other Bounds

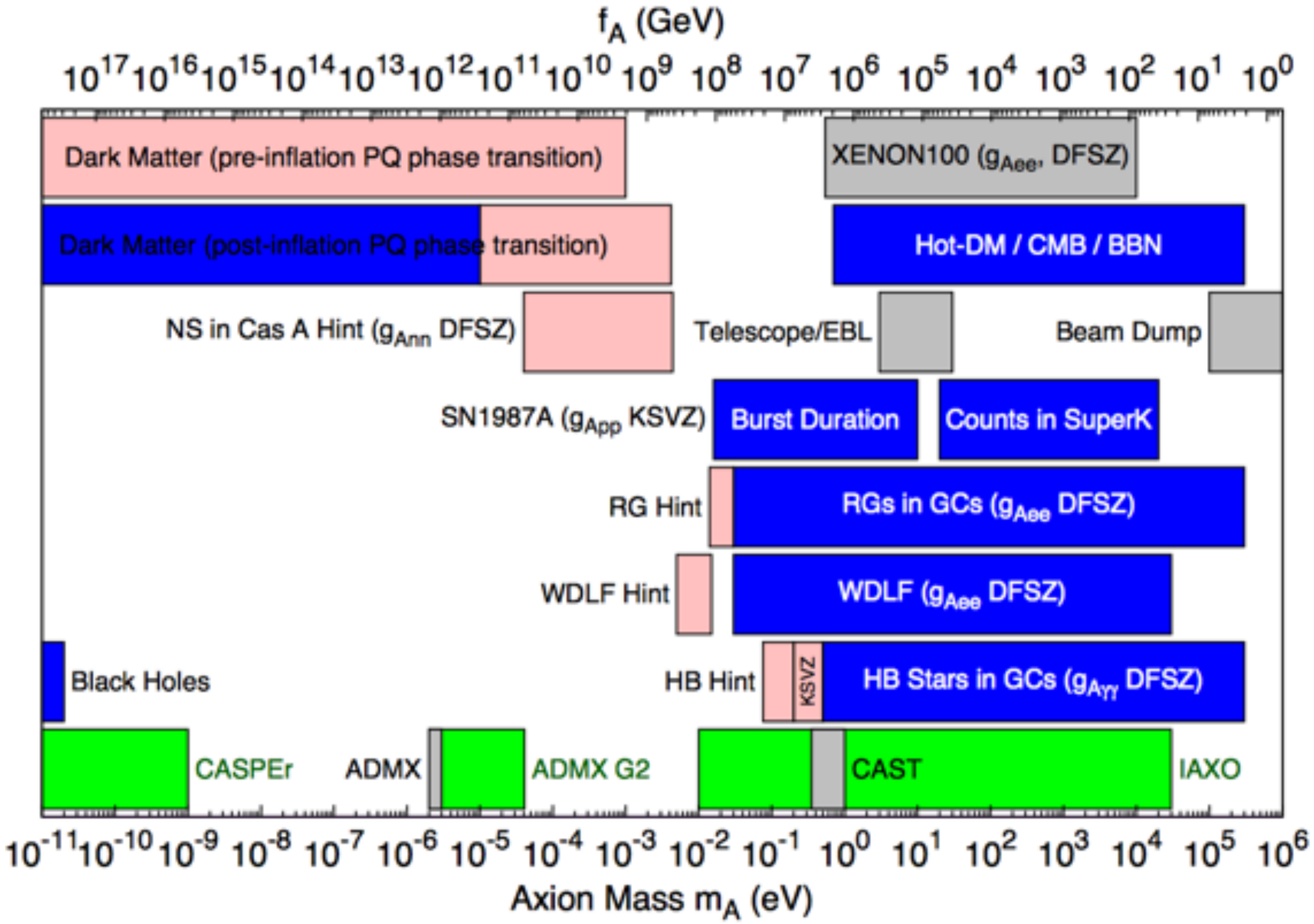
- CAST
- Beam dump
- Solar ν flux
- Horizontal Branch
- BBN
- Supernova 1987a

Collider Bounds

- LHC @ 7 TeV: mono-γ, 5 fb^{-1}
- LHC @ 8 TeV: mono-γ, 19.6 fb^{-1}
- LEP @ M_Z: tri-γ, 66 pb^{-1}
- LEP @ 189 GeV: tri-γ, 153 pb^{-1}
- CDF: 3-γ, 1.2 fb^{-1}
- LEP: mono-γ

Future Reach

- ILC @ 240 GeV, 1 ab^{-1}
- TLEP @ 1 TeV, 10 ab^{-1}
- Belle II @ 10.6 GeV, 50 ab^{-1}
- LHC @ 13 TeV: mono-γ, 3 ab^{-1}
- LHC @ 13 TeV: tri-γ, 3 ab^{-1}
- LHC @ 8 TeV: tri-γ, 19.6 fb^{-1}



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 $\cos^2 \beta' = 1/2$.

Higgs EFTs

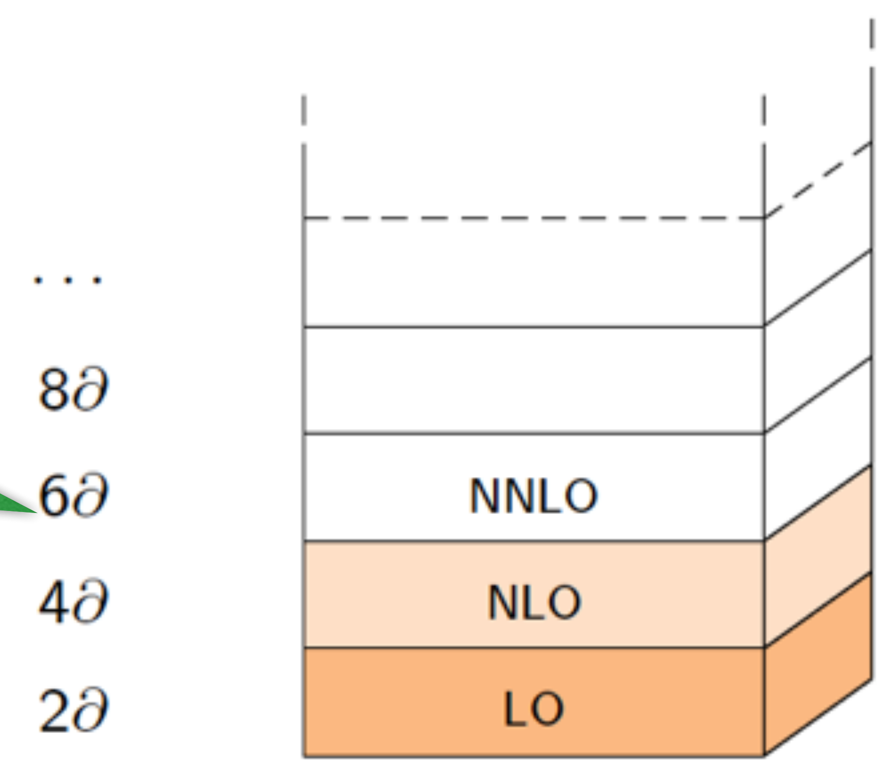
Linear or **Chiral** (non-linear)

in chiral: $\phi \to \mathbf{F(h)}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

Godstone bosons = $e^{i\pi^a\sigma^a/v}$

U adimensional

Expansion in derivatives: D_μ/Λ :



In EFT, the weight of **h** is arbitrary
we use **h**/v, but the conclusions
would be the same with **h**/f