

Axions and Axion-like Particles

Belén Gavela
Univ. Autónoma de Madrid and IFT

MORIOND Electroweak 2017



H2020 elusives

inVisiblesPlus

We will consider the SM plus a generic scalar field a

with derivative couplings to SM particles

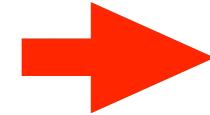
and free scale f_a :

an ALP (axion-like particle)

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

general effective couplings

This is shift symmetry invariant: $a \rightarrow a + \text{cte.}$



~ Goldstone
boson

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general effective couplings

Why?

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

Or simply the first one discovered?

The spin 0 window



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

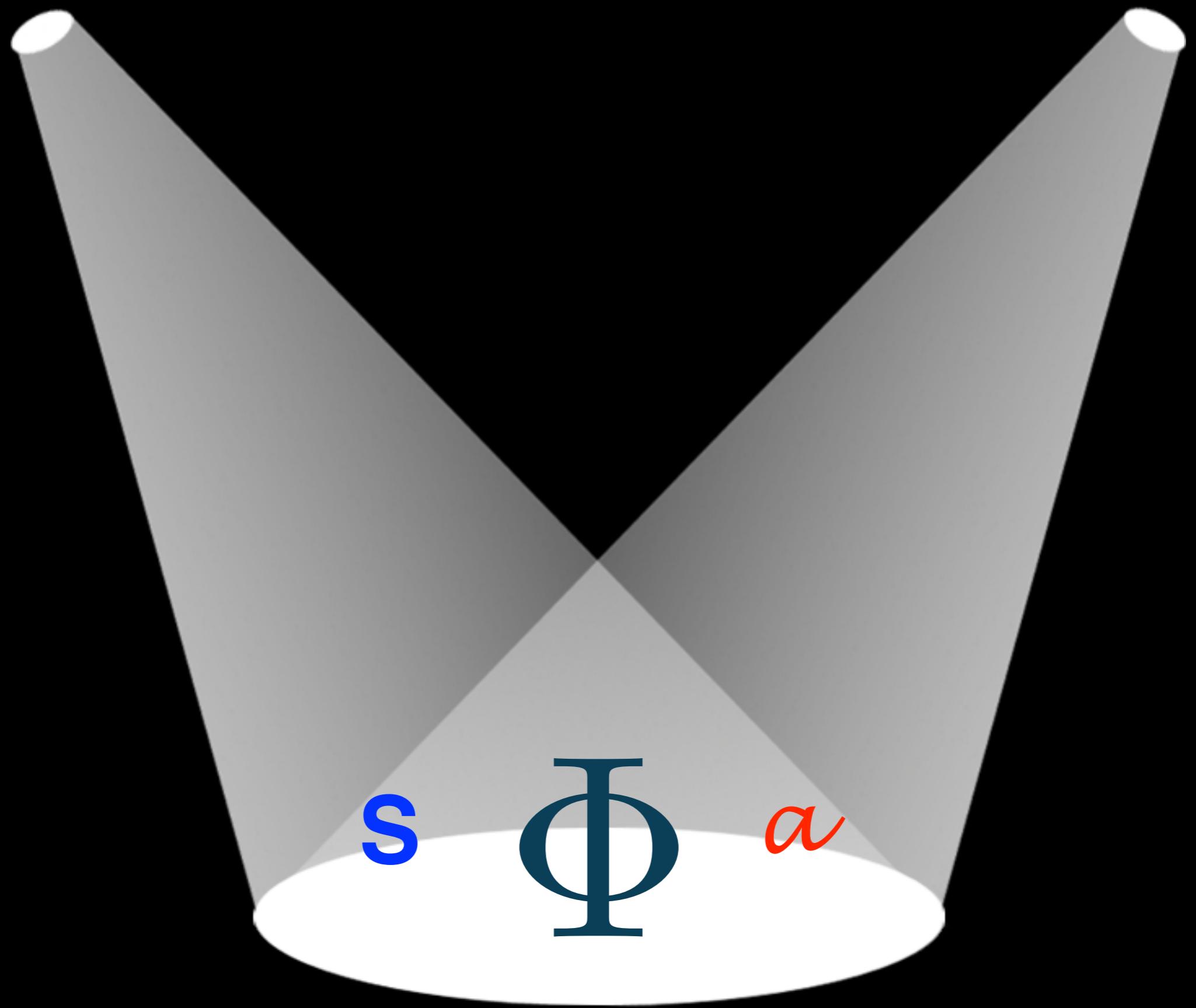
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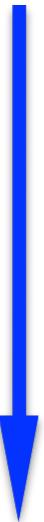
What about a singlet (pseudo) scalar?

Strong motivation from fundamental problems of the SM



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

The nature of DM is unknown



It may be a (SM singlet) scalar **S**

the “Higgs portal”

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

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

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 thick red vertical arrow pointing downwards, indicating a flow or connection from the top text to the bottom text.

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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Also excellent DM candidate

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



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)

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

QCD

$m_q \langle \bar{\Psi} \Psi \rangle \simeq m_\pi^2 f_\pi^2$

$\Lambda \gg m_q$

$\Lambda \ll m_q$

Λ^4

Choi et al. 1986

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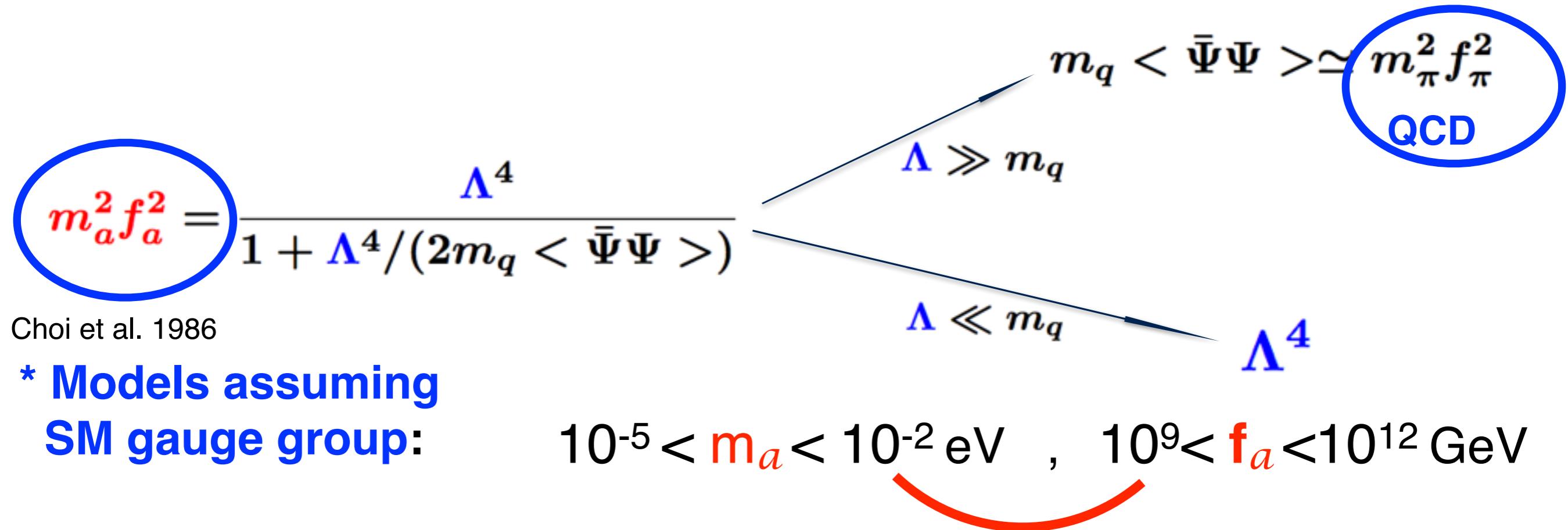
Choi et al. 1986

* Models assuming
SM gauge group: $10^{-5} < m_a < 10^{-2}$ eV , $10^9 < f_a < 10^{12}$ GeV

m_a vs scale f_a

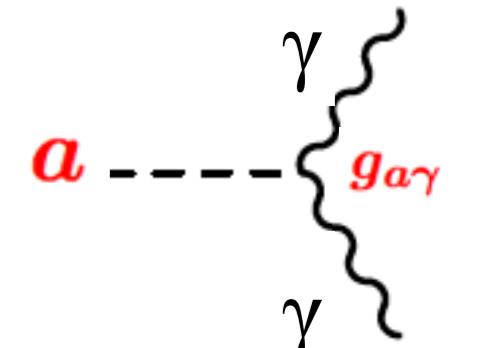
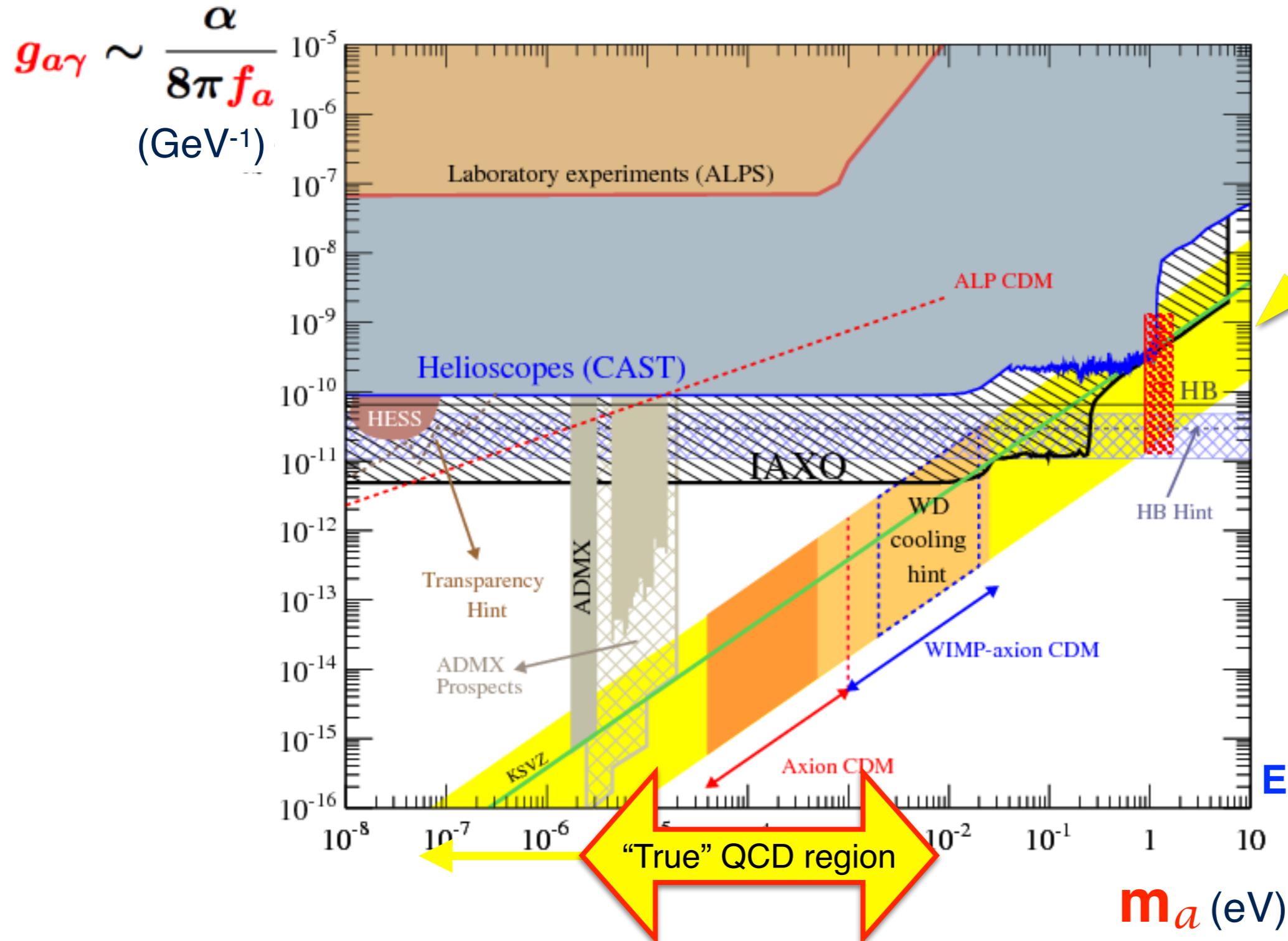
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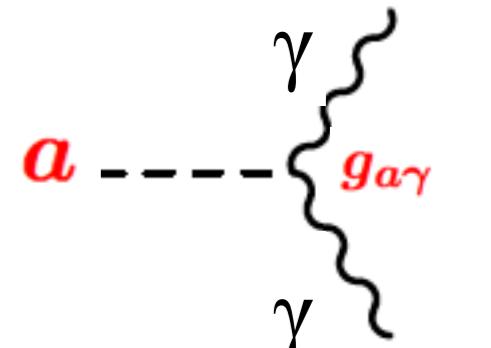
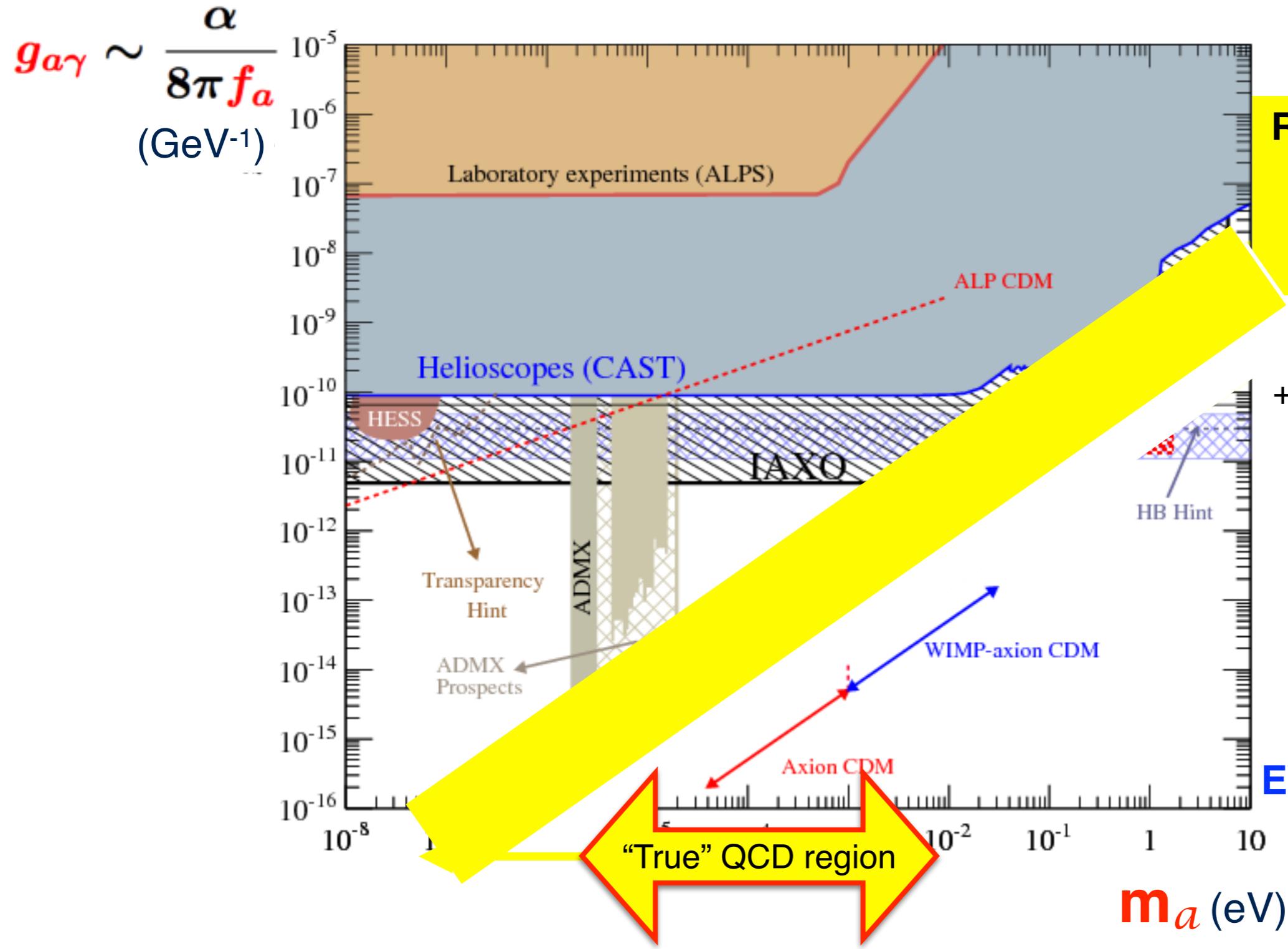


* Models assuming
SM gauge group:

Intensely looked for experimentally...



... and theoretically



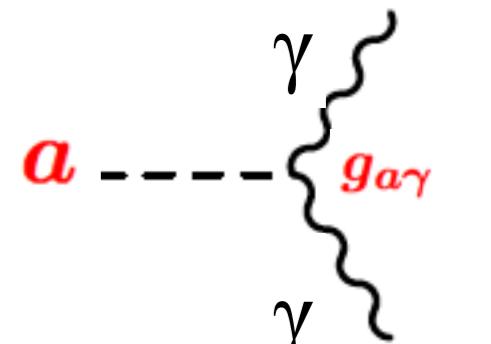
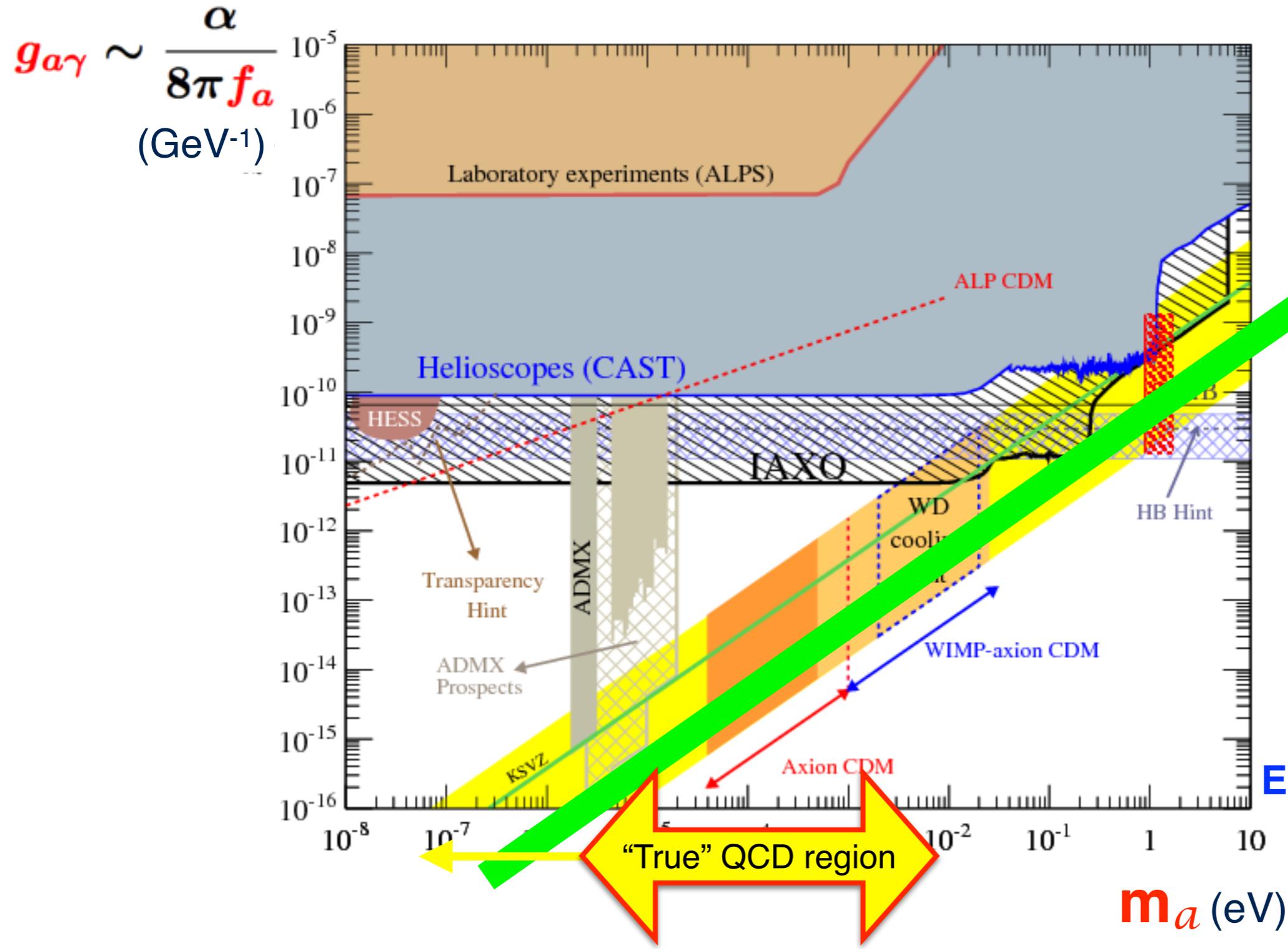
**Refined KSVZ axion band:
up and thinner**

**from Ω_{DM}
+ Landau-poles analysis
(Luzio+Mescia+Nardi 2017)**

$v \ll f_a \rightarrow$
EW hierarchy problem

m_a (eV)

... and theoretically

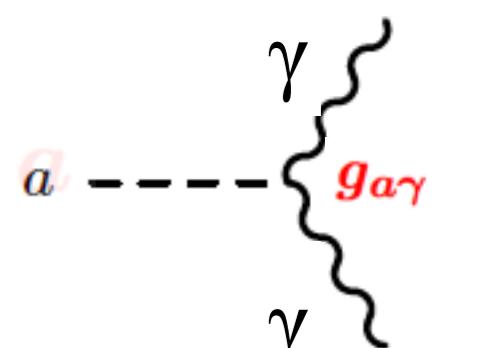
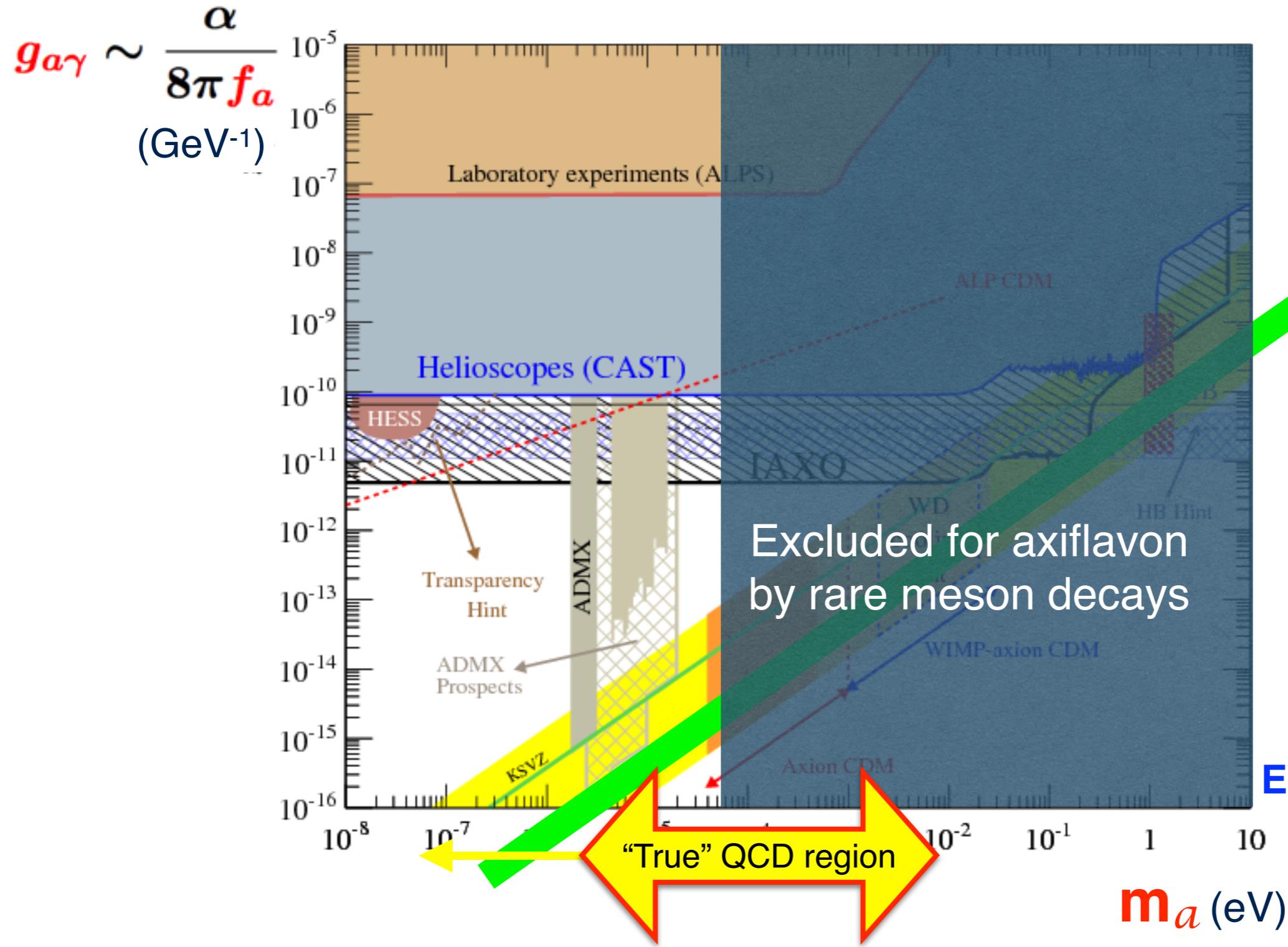


QCD axiflavor band
 (creative view)

(Calibbi et al. 2016)

$v \ll f_a \rightarrow$
EW hierarchy problem

... and theoretically

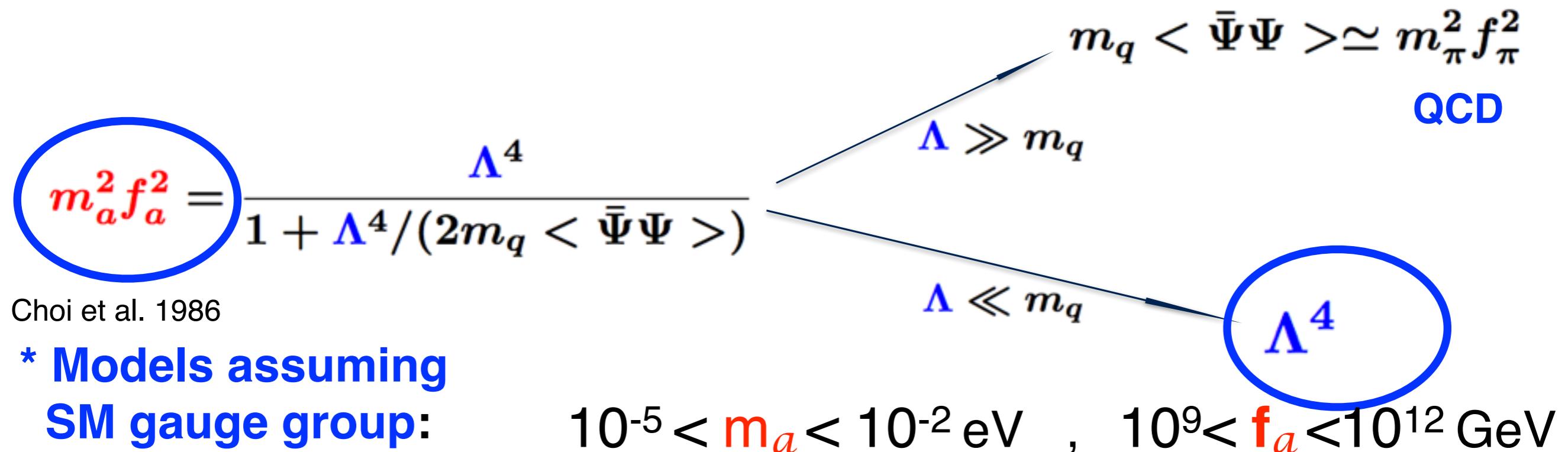


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$$m_a^2 f_a^2 = \text{QCD part} + \Lambda'^4 , \quad \Lambda' \gg \Lambda_{\text{QCD}}$$

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m_a vs scale f_a

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The diagram illustrates the relationship between the parameters $m_a^2 f_a^2$, Λ^4 , and $m_q \langle \bar{\Psi} \Psi \rangle$ in a QCD-like theory. A central equation is given by:

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

Two arrows point from the term $\Lambda^4 / (2m_q \langle \bar{\Psi} \Psi \rangle)$ to the right side of the equation. The top arrow is labeled $\Lambda \gg m_q$ and leads to the expression $m_q \langle \bar{\Psi} \Psi \rangle \simeq m_\pi^2 f_\pi^2$. The bottom arrow is labeled $\Lambda \ll m_q$ and leads to the expression Λ^4 . Below the equation, the text "Choi et al. 1986" is written.

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

$\Lambda \gg m_q \quad m_q \langle \bar{\Psi} \Psi \rangle \simeq m_\pi^2 f_\pi^2$

$\Lambda \ll m_q \quad \Lambda^4$

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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., Khobadze...

Hook and many collaborators, Dimopoulos et al. ...

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



$$\Lambda' \gg \Lambda_{\text{QCD}}$$

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

* The ugly part: θ and θ'

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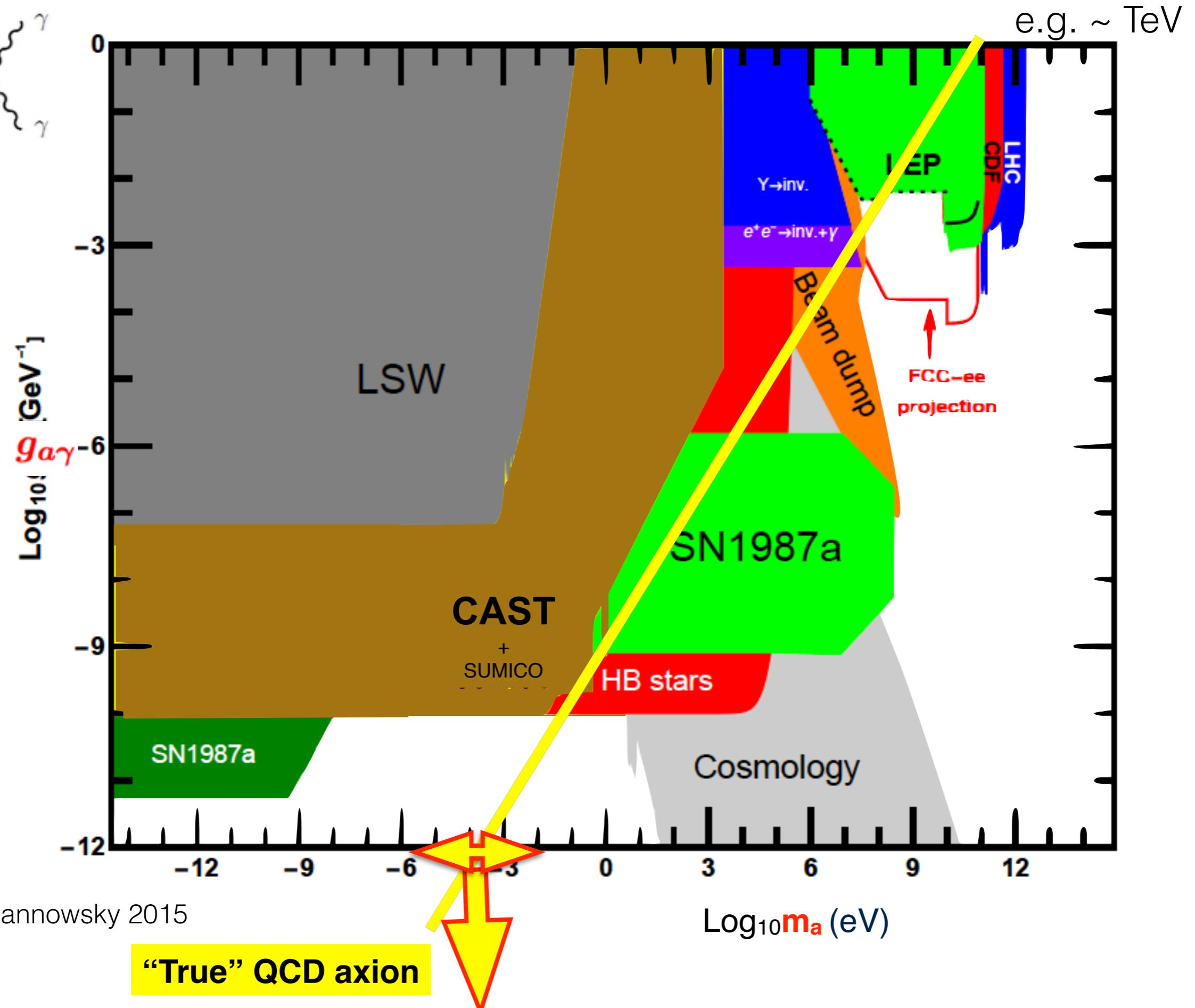
* The ugly part: θ and θ'

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

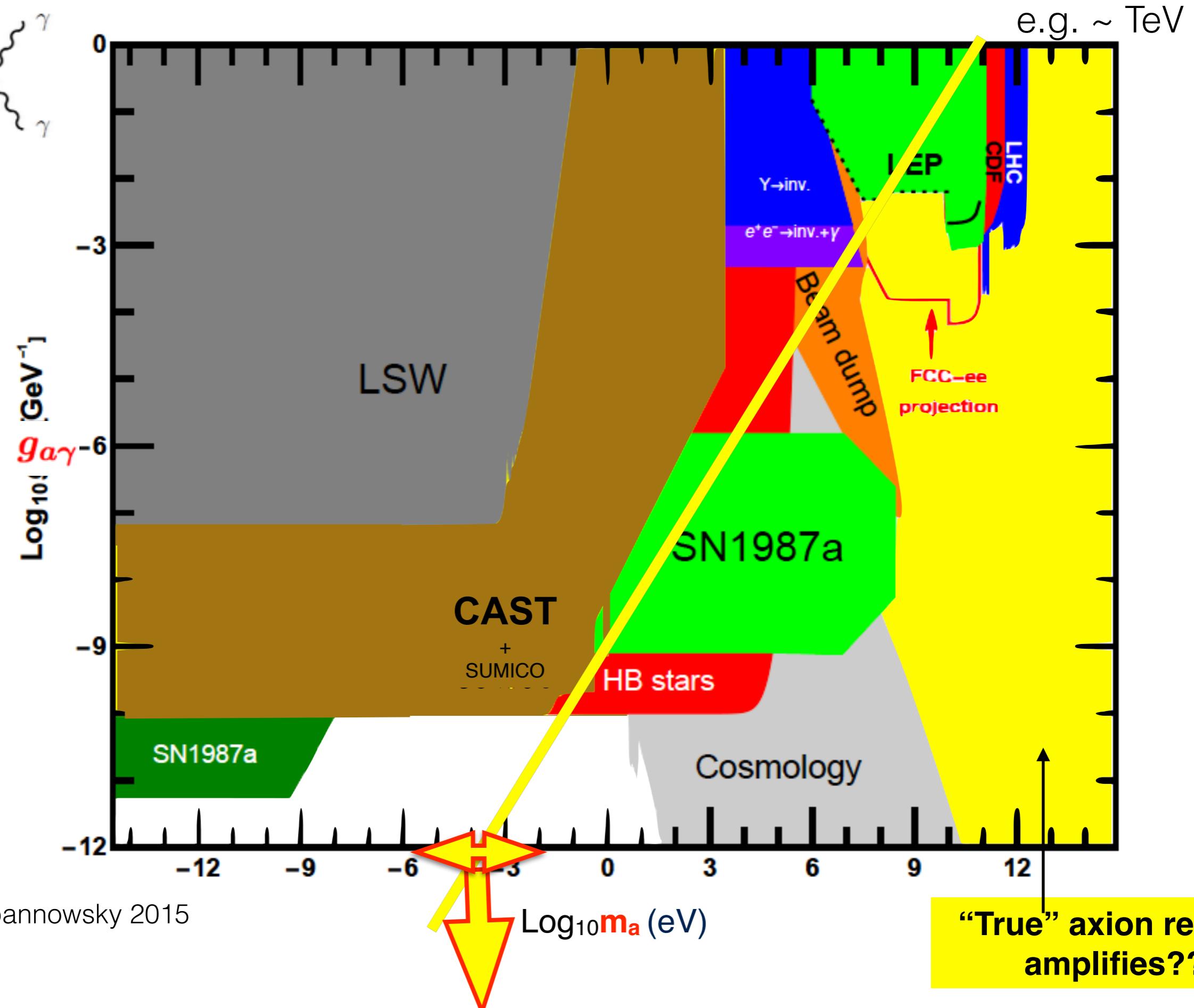
Nothing works very nicely, but there is movement

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

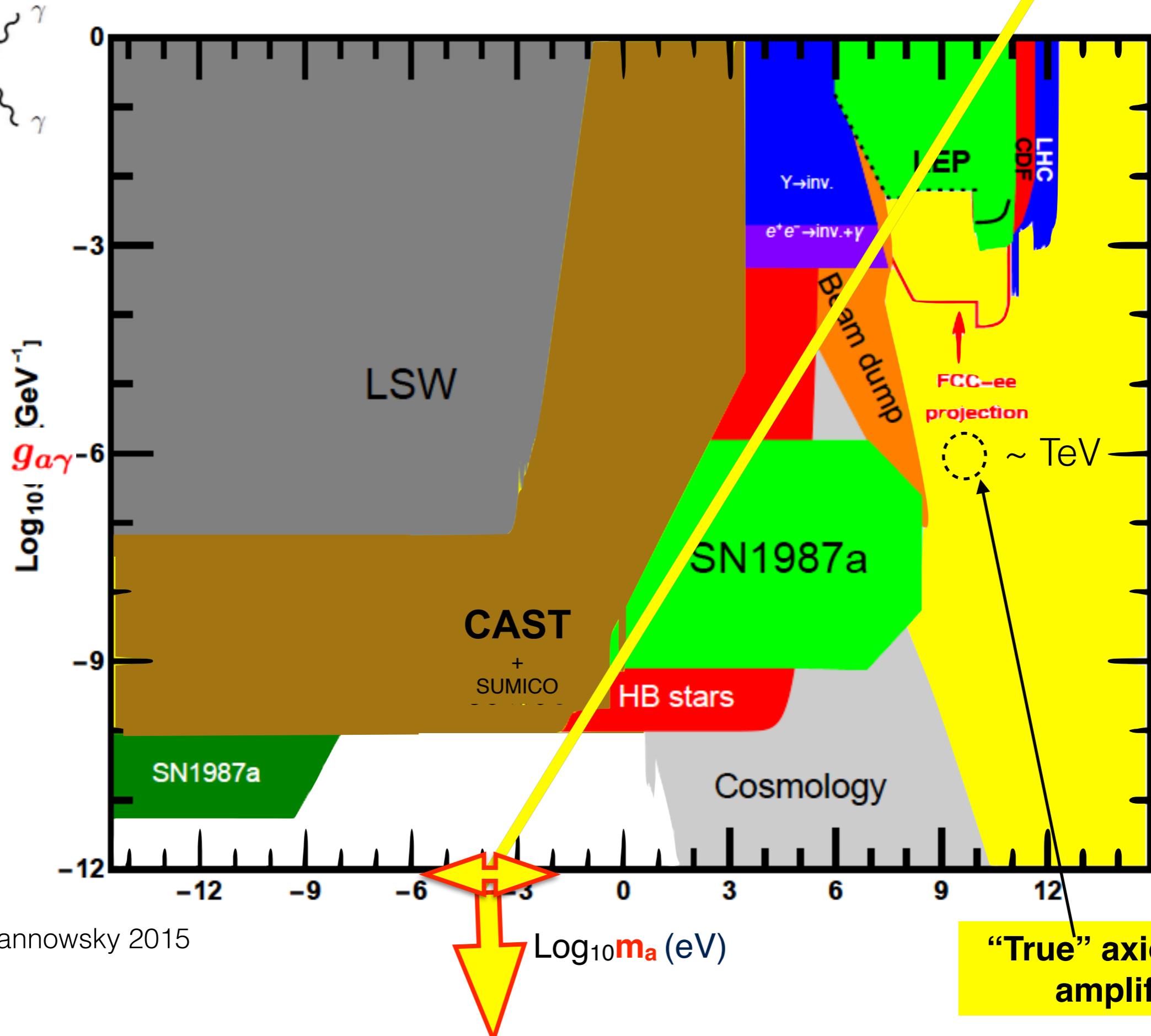
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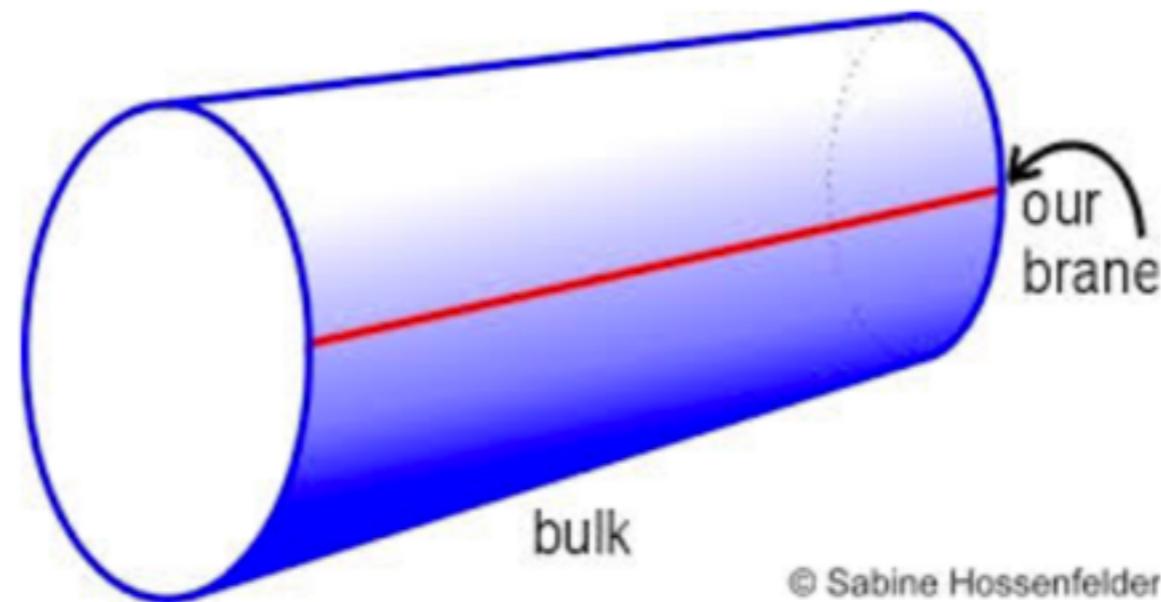


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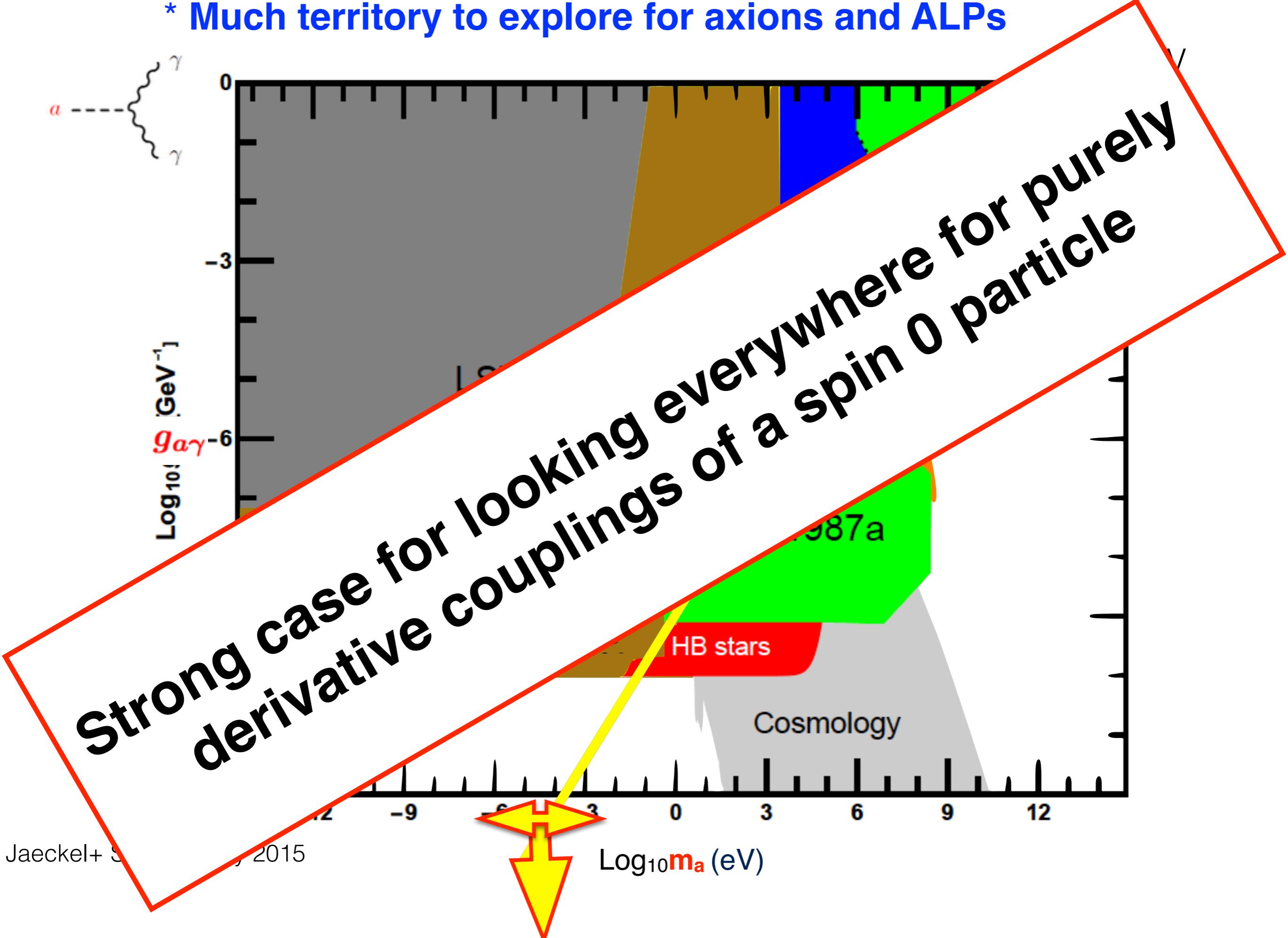
(Pseudo)Goldstone Bosons also in many BSM theories

- * 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 Moriond example: the “relaxion” (G. Perez talk) is not a GB but part of its couplings are purely derivative as those of ALPs, e.g. $\phi W_{\mu\nu} \tilde{W}^{\mu\nu}$

* Much territory to explore for axions and ALPs



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with derivative couplings to SM particles

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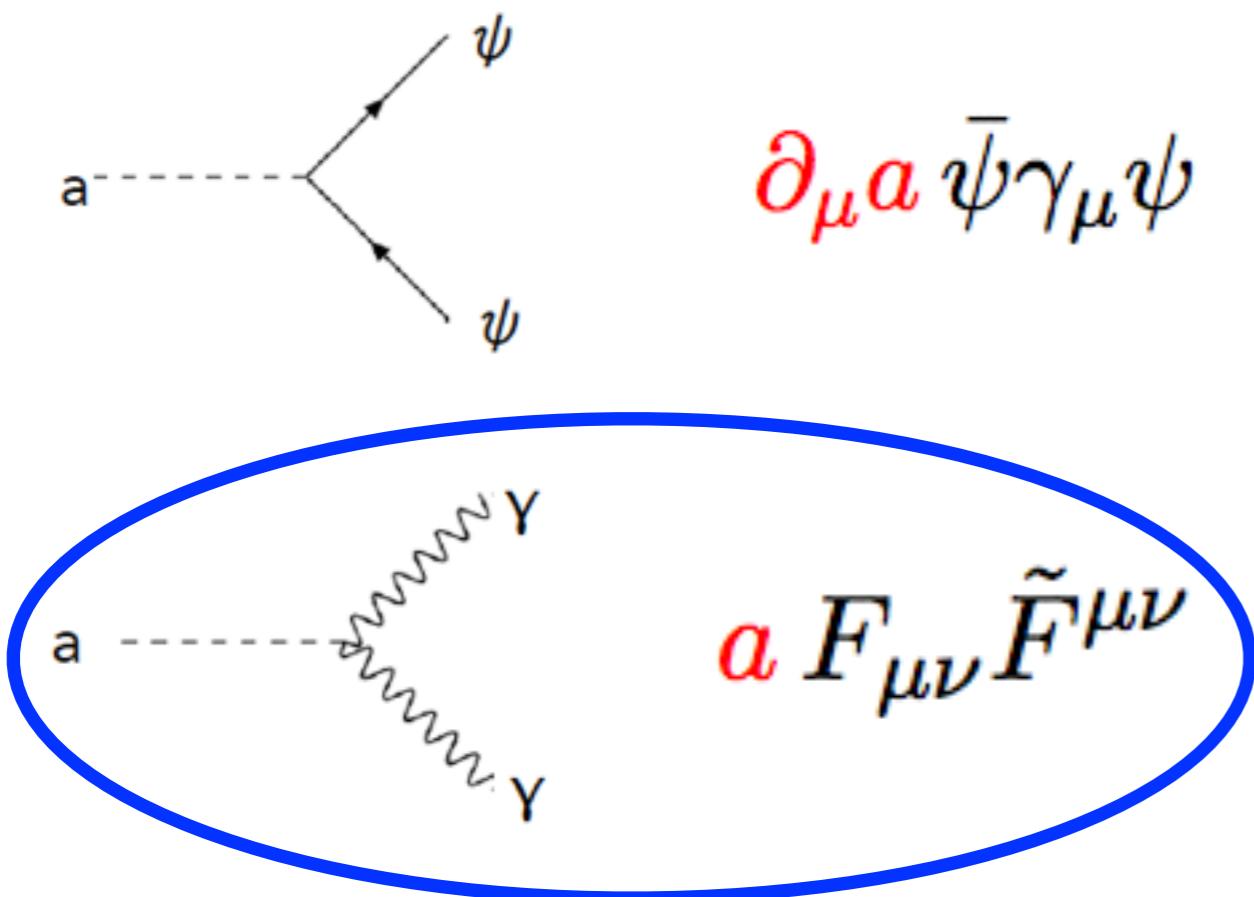
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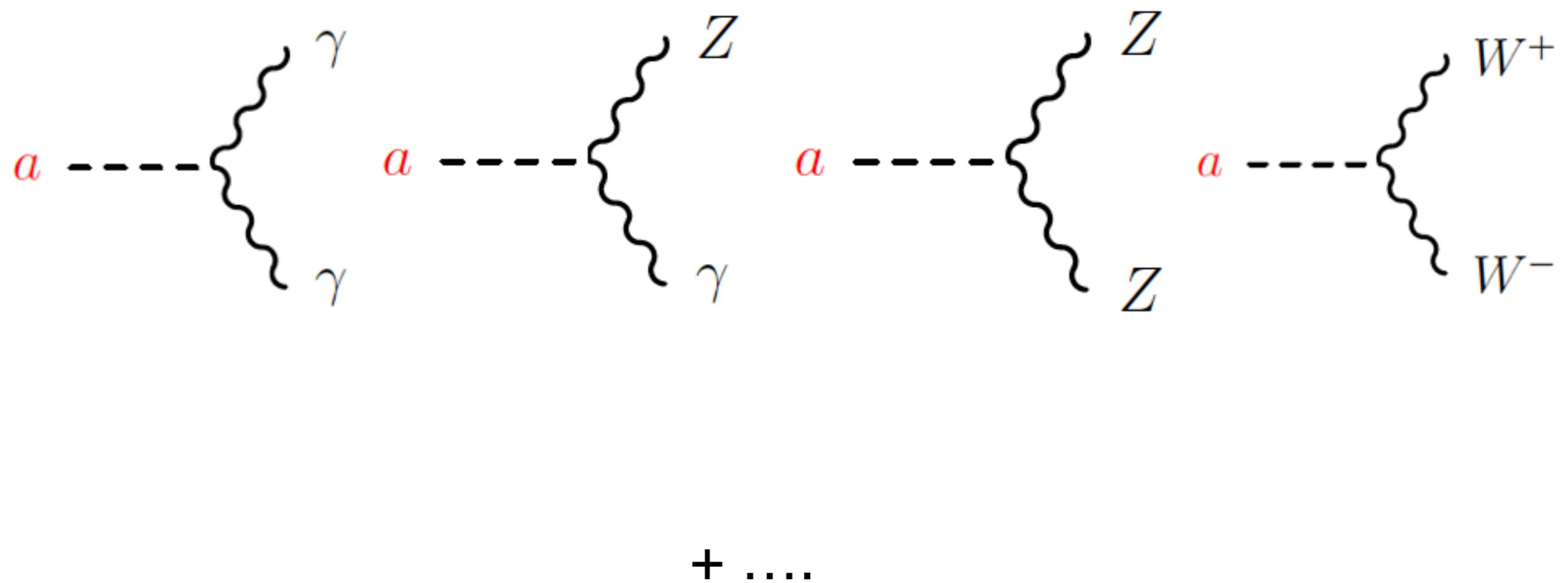
general effective couplings

THEORY plus NEW SIGNALS at colliders

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



**But because of $SU(2) \times U(1)$ gauge invariance,
 $a\text{-}\gamma\gamma$ should come together with $a\text{-}\gamma Z$, $a\text{-}ZZ$ and $a\text{-}W^+W^-$:**



ALP-Linear effective Lagrangian at NLO

II
SM EFT

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

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

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

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SM higgs doublet

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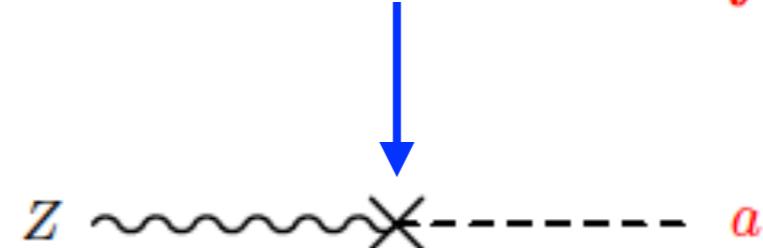
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$\Phi \rightarrow e^{ic_{a\Phi} a/f_a} \Phi$

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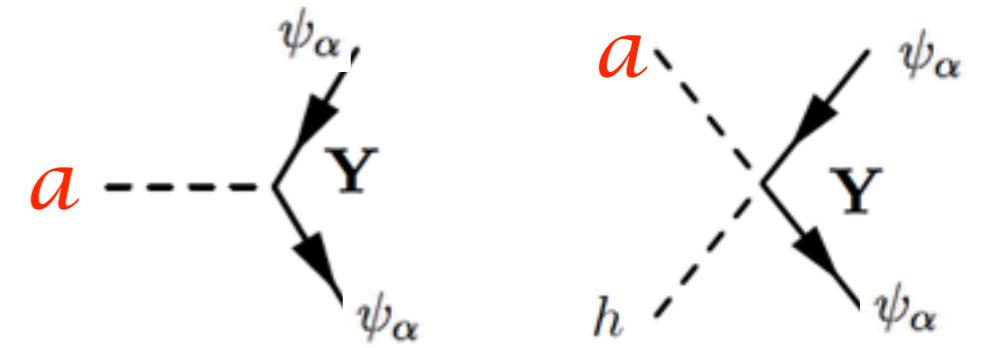
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Only fermionic a -Higgs couplings

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Note: NO a -Higgs purely bosonic couplings

ALP-Linear effective Lagrangian at NLO

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Complete basis (bosons+fermions):

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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

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analysis parameters:

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

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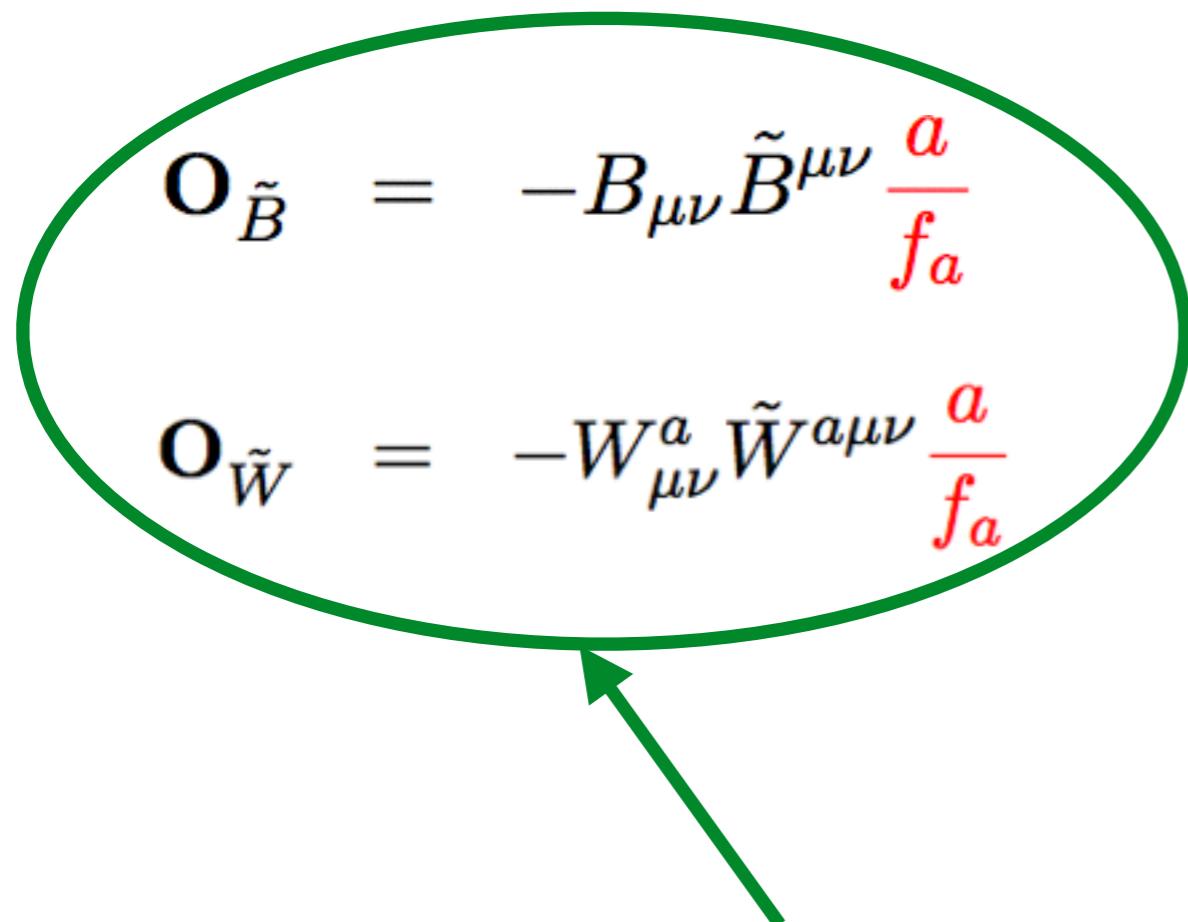
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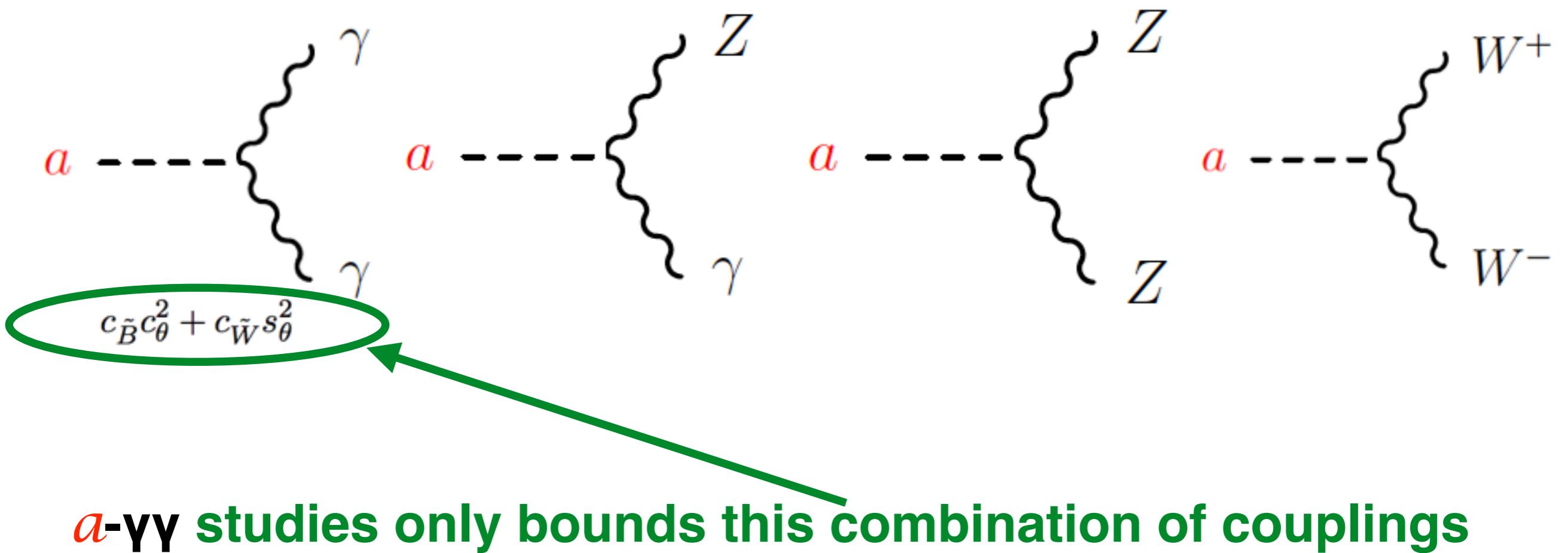
contain a - $\gamma\gamma$ and other couplings

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Salvio + Strumia + Shue, 2013

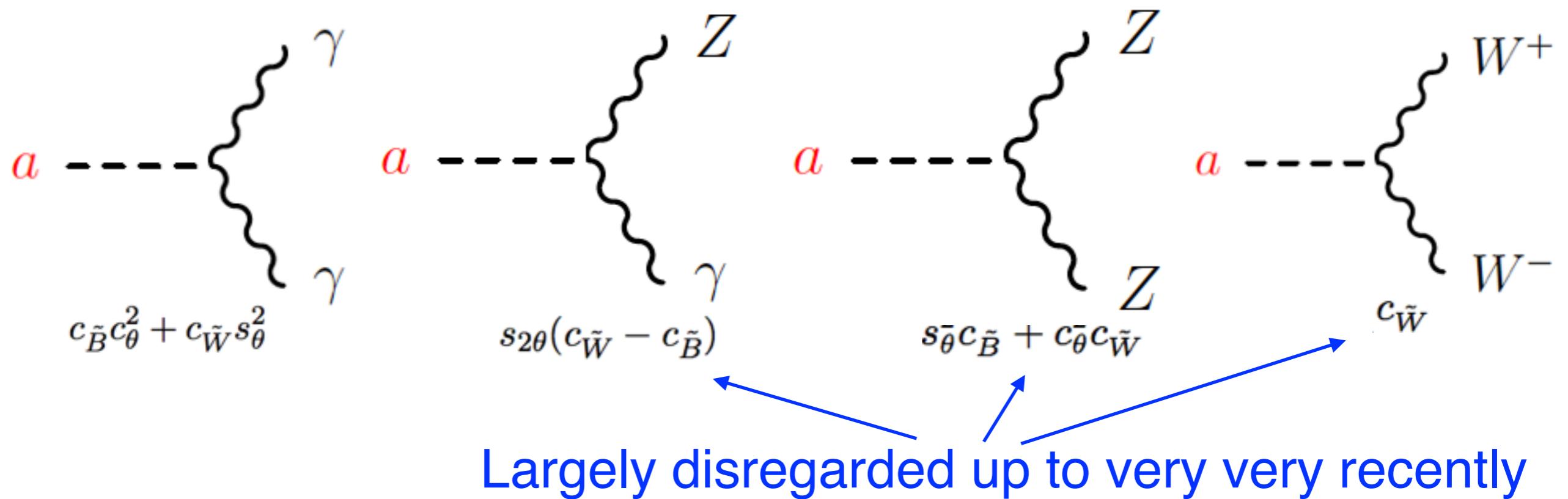
**Because of $SU(2) \times U(1)$ gauge invariance,
 $a\text{-}\gamma\gamma$ comes together with $a\text{-}\gamma Z$, $a\text{-}ZZ$ and $a\text{-}W^+W^-$:**



90% CL: $|c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2| \lesssim$

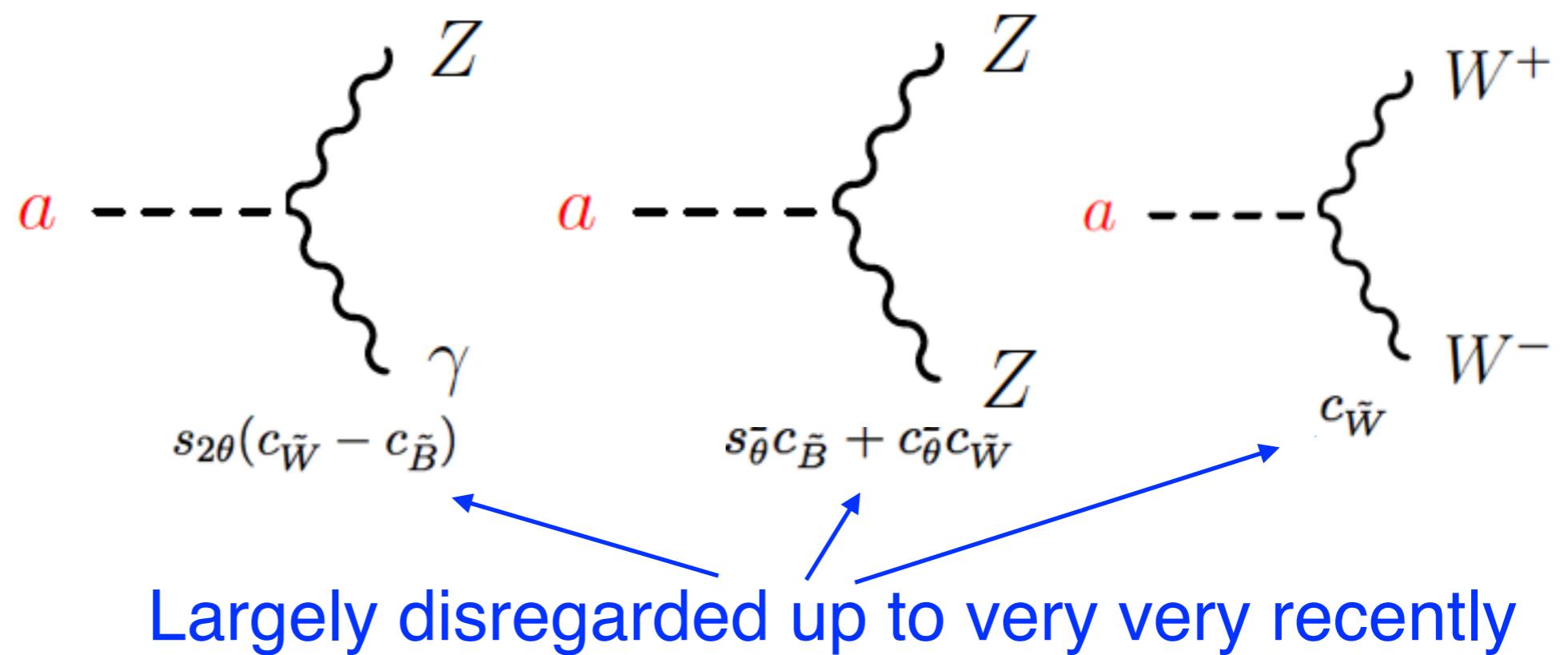
0.0025 (f_a/TeV)	$m_a \leq 1 \text{ MeV}$
$2.5 \cdot 10^{-8}$ (f_a/TeV)	$m_a \leq 1 \text{ keV}$

**Because of $SU(2) \times U(1)$ gauge invariance,
 $a\text{-}\gamma\gamma$ comes together with $a\text{-}\gamma Z$, $a\text{-}ZZ$ and $a\text{-}W^+W^-$:**



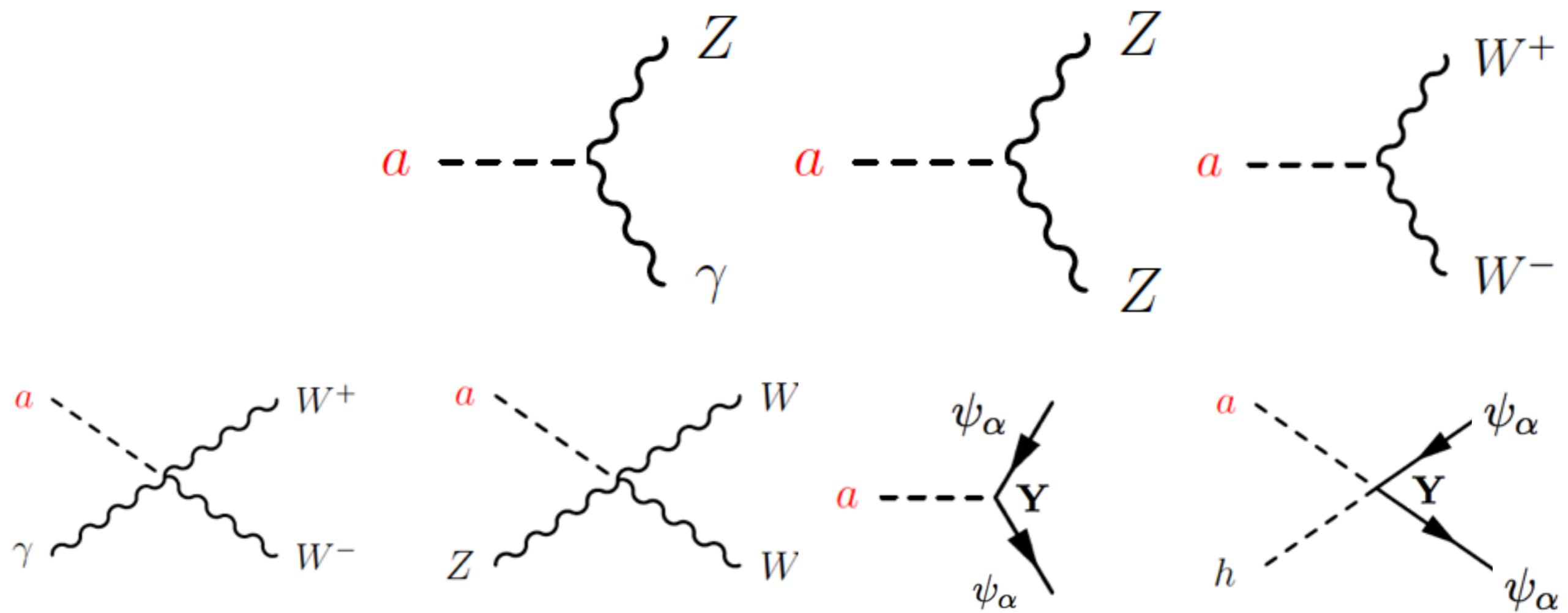
only a tiny bit in Jaeckel+Spannowsky 2015

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



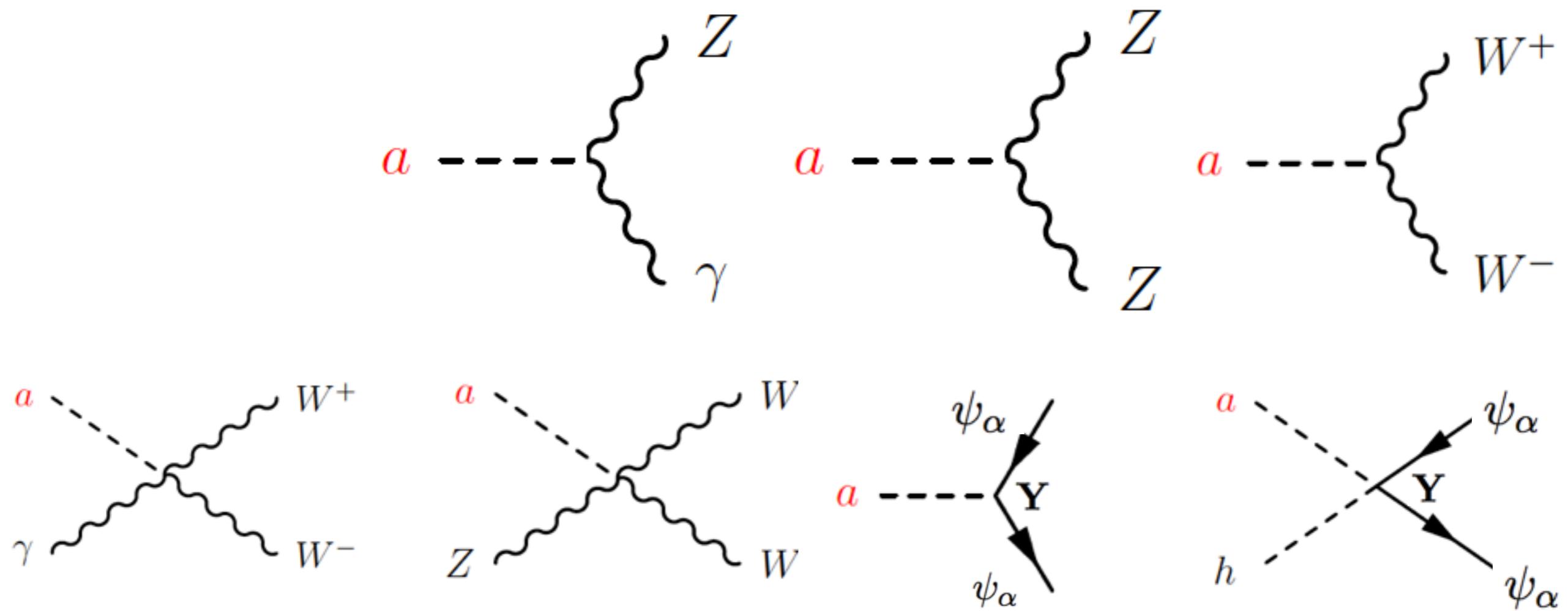
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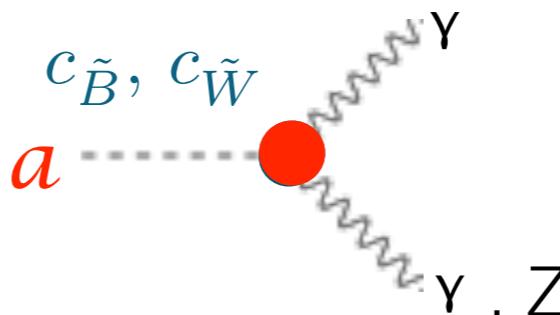
→ New signals: mono-Z, mono-W, associated $aW\gamma$, $a\bar{t}t$



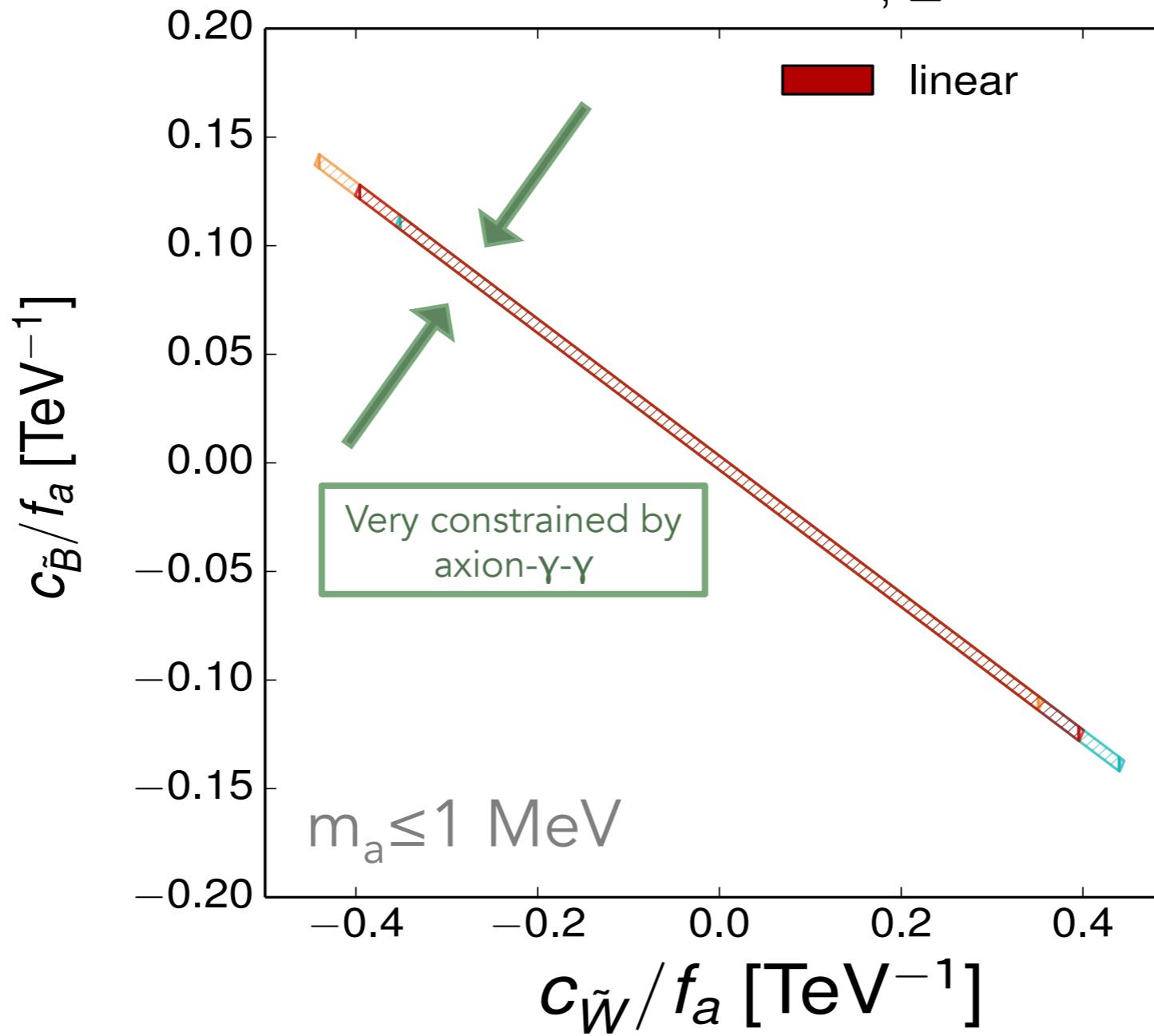
Accelerator constraints on $a\text{-}\gamma\text{-}\gamma$ and $a\text{-}\gamma\text{-}Z$

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

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



LEP impact

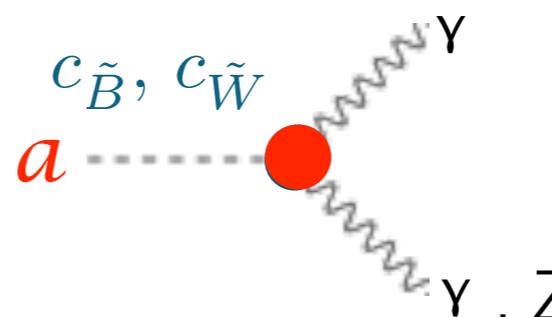


$m_a \leq 1 \text{ MeV}$

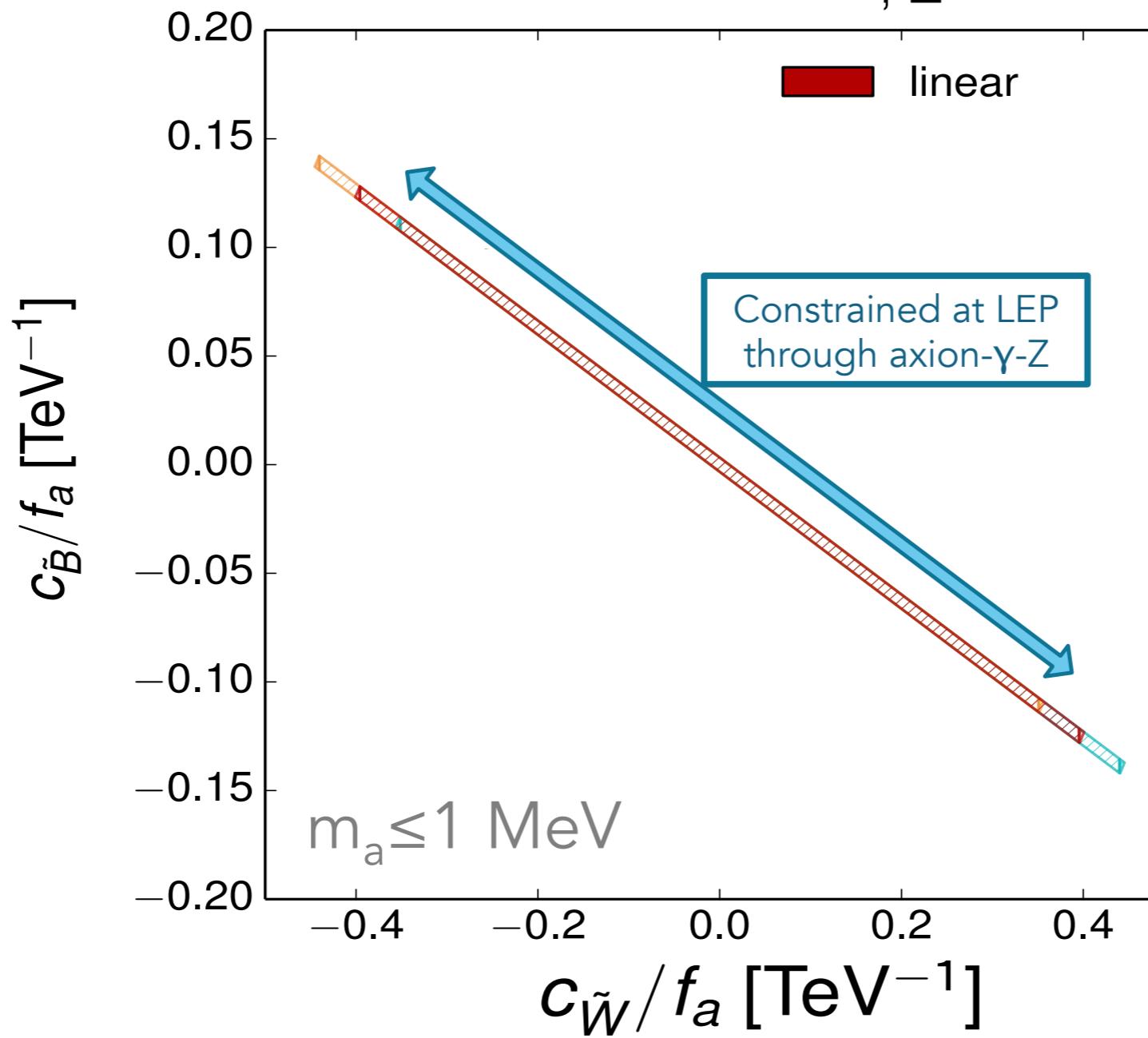
Accelerator constraints on a - γ - γ and a - γ - Z

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

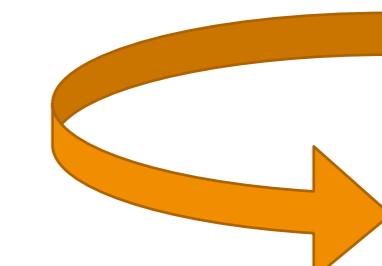
$$\mathbf{O}_{\tilde{W}} = -W_{\mu\nu}^a \tilde{W}^{a\mu\nu} \frac{a}{f_a}$$



LEP impact

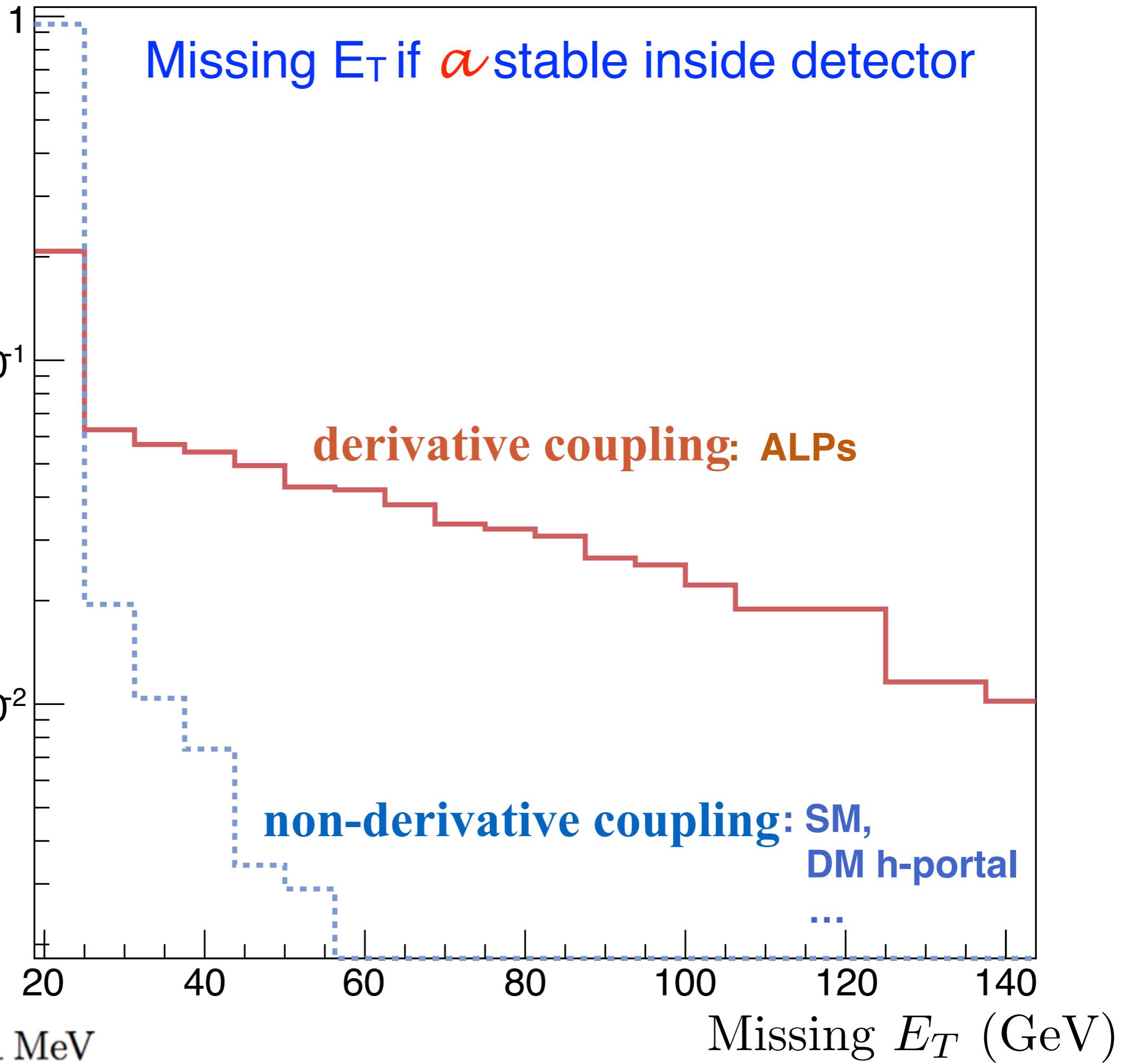


$$\rightarrow \left| \frac{f_a}{c_{\tilde{W}}} \right| > 2.38 \text{ TeV}$$



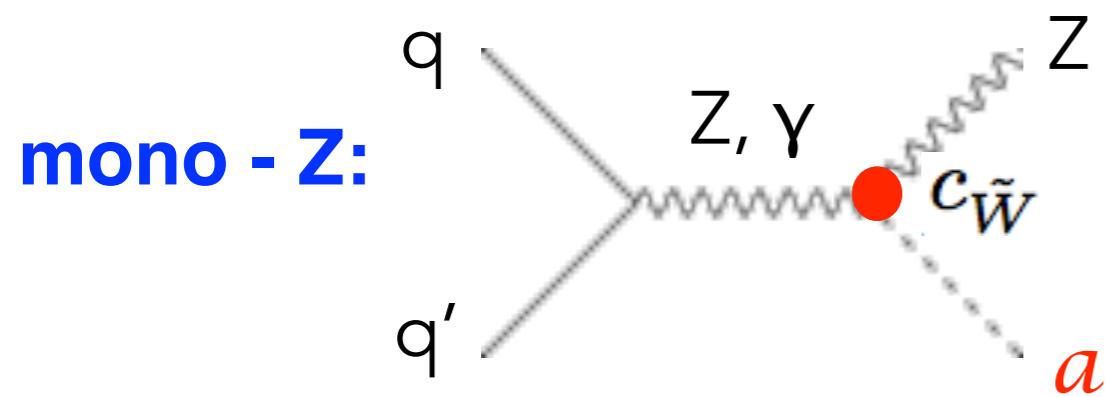
+ even more at LHC!

$$\frac{1}{\sigma} \frac{d\sigma}{d \text{ MET}}$$

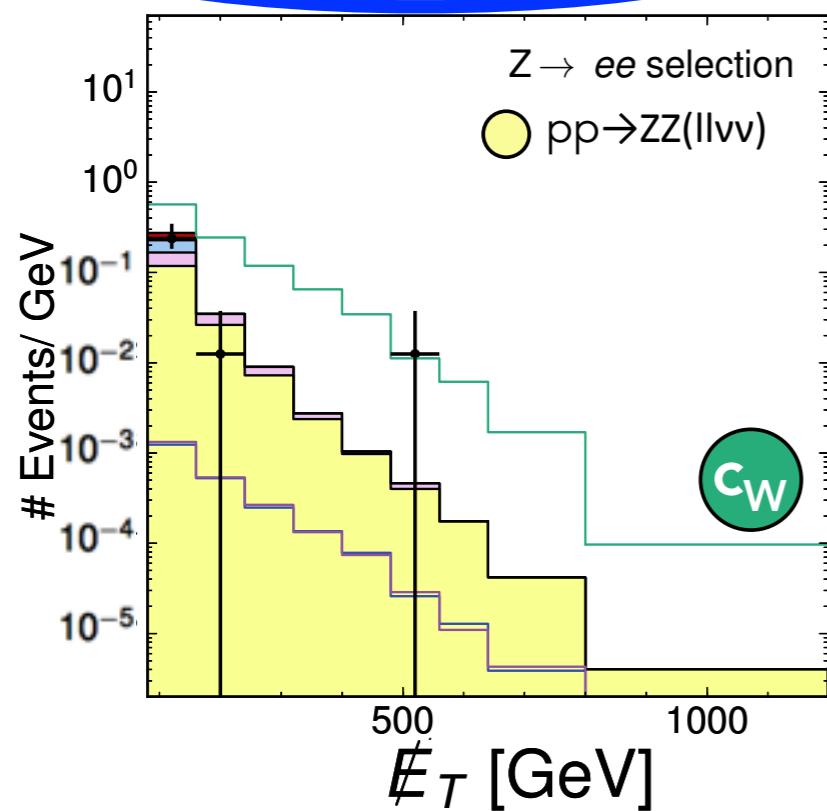


e.g. for $m_a \leq 1 \text{ MeV}$

Mono - Z and mono - W ALP signals

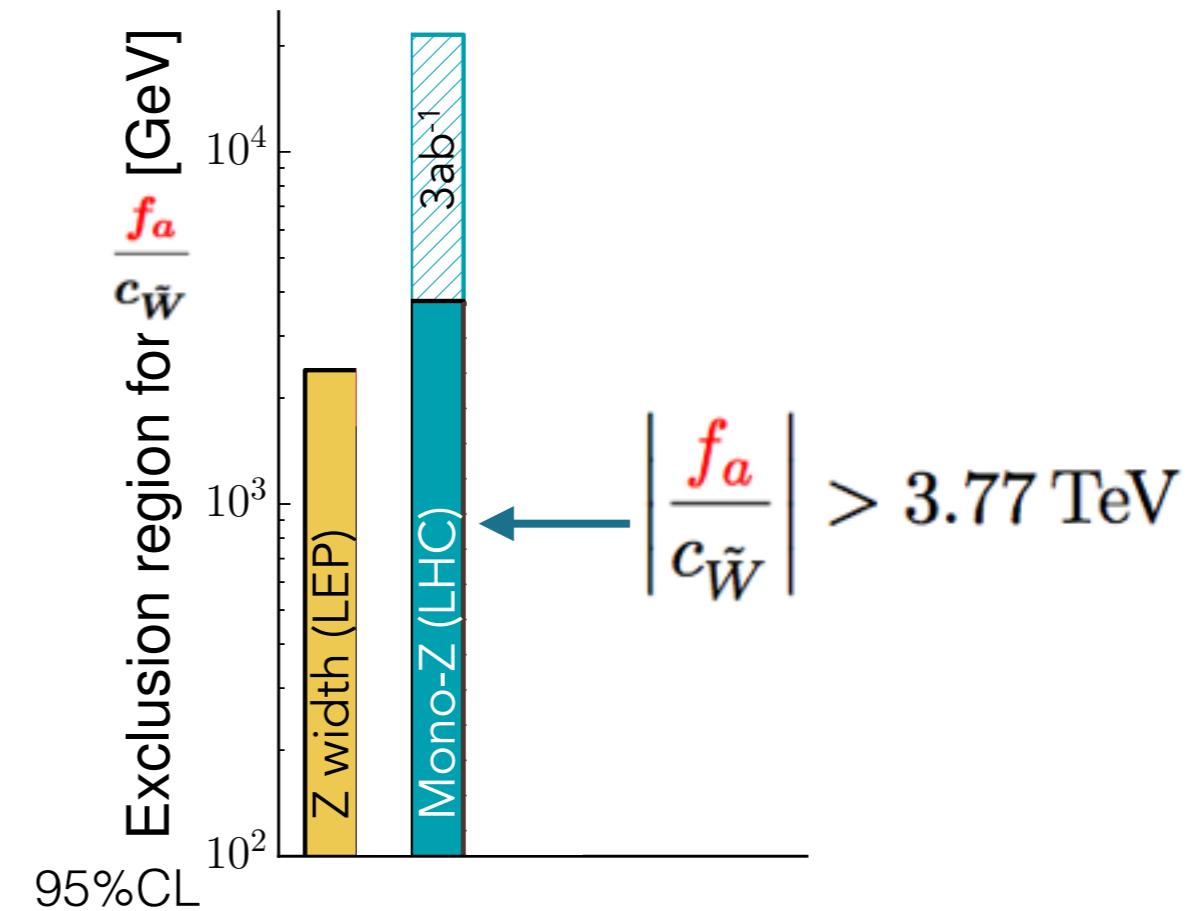
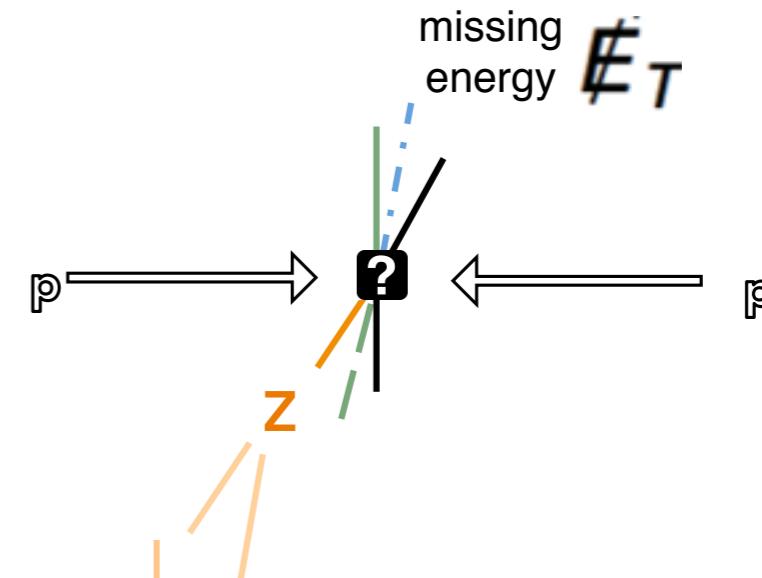


e.g. $\mathbf{O}_{\tilde{W}} = -W_{\mu\nu}^a \tilde{W}^{a\mu\nu} \frac{a}{f_a}$



13 TeV 2.3 fb^{-1} CMS $Z + E_T$

$E_T > 80 \text{ GeV}$ $p_T^\ell > 20 \text{ GeV}$, $|\eta_\ell| < 2.5$, $p_T^{\ell\ell} > 50$

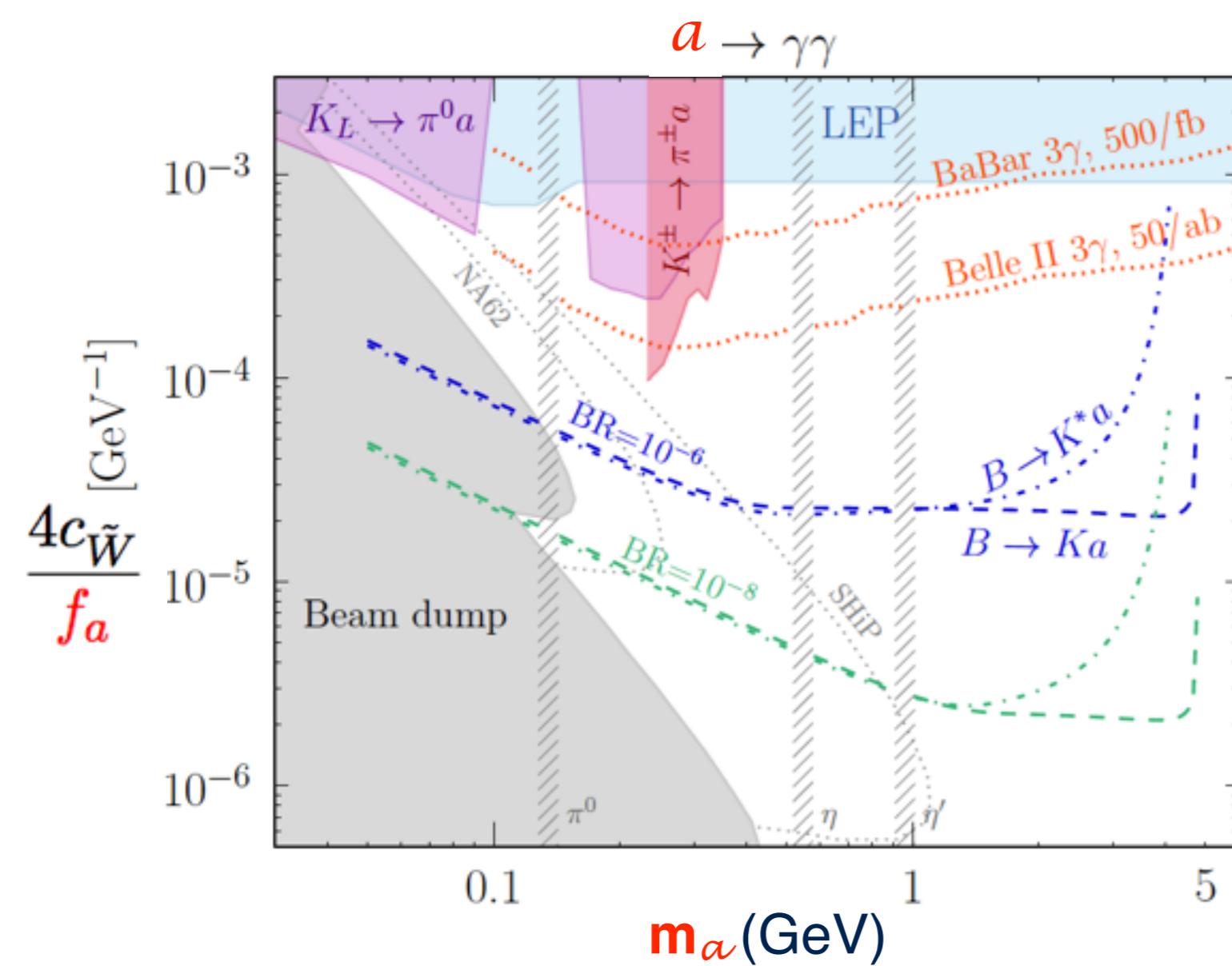
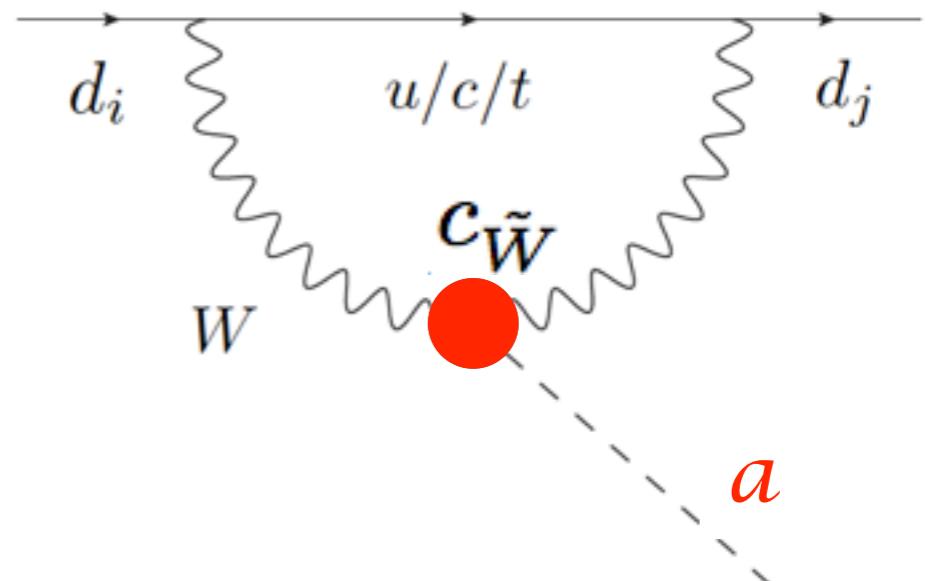


3ab⁻¹: assuming no improvement in systematics

Interesting very recent development:

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

$B \rightarrow K \alpha$, $K \rightarrow \pi \alpha \dots \alpha \rightarrow \gamma\gamma$



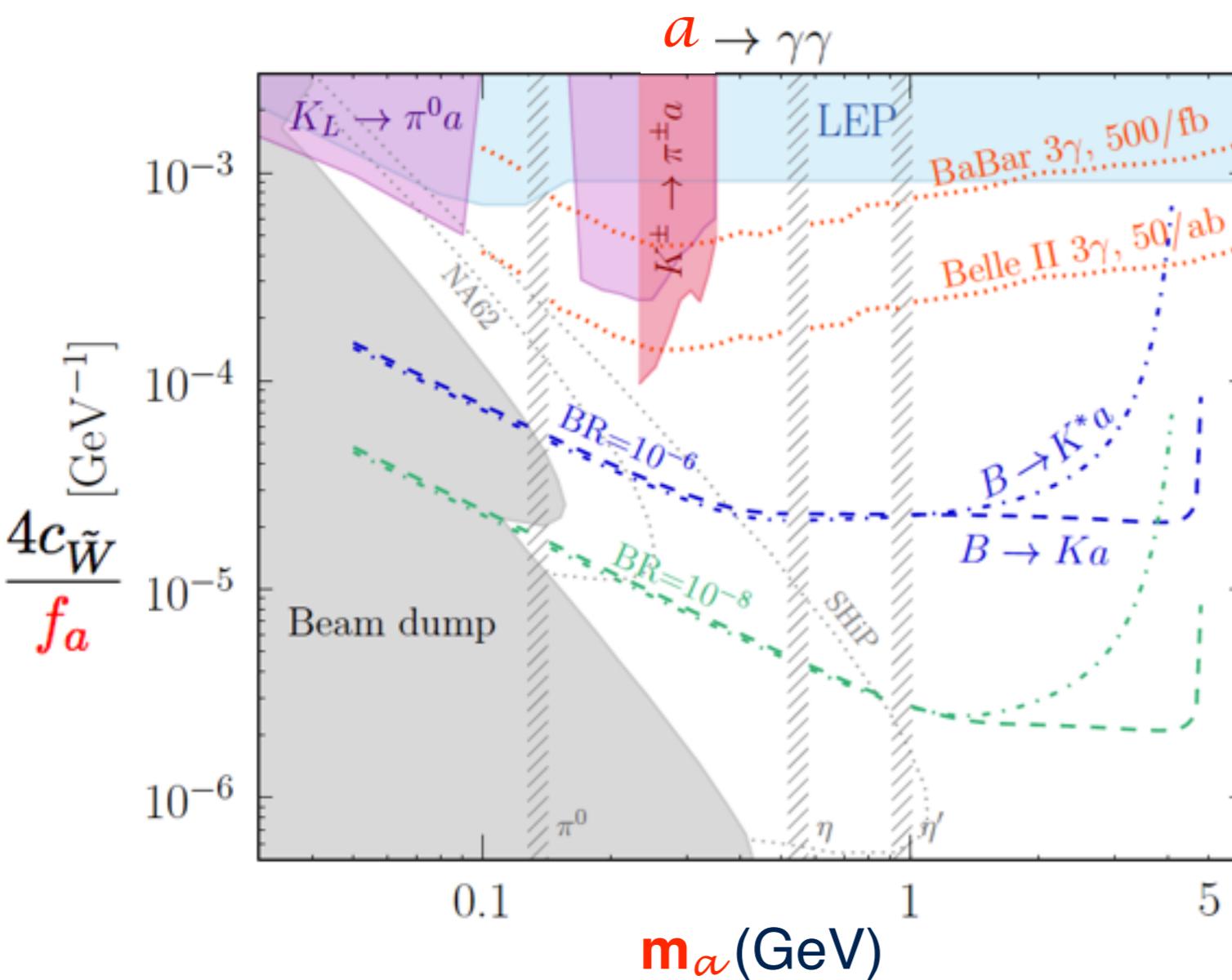
Izaguirre+Lin+Shuve 2016



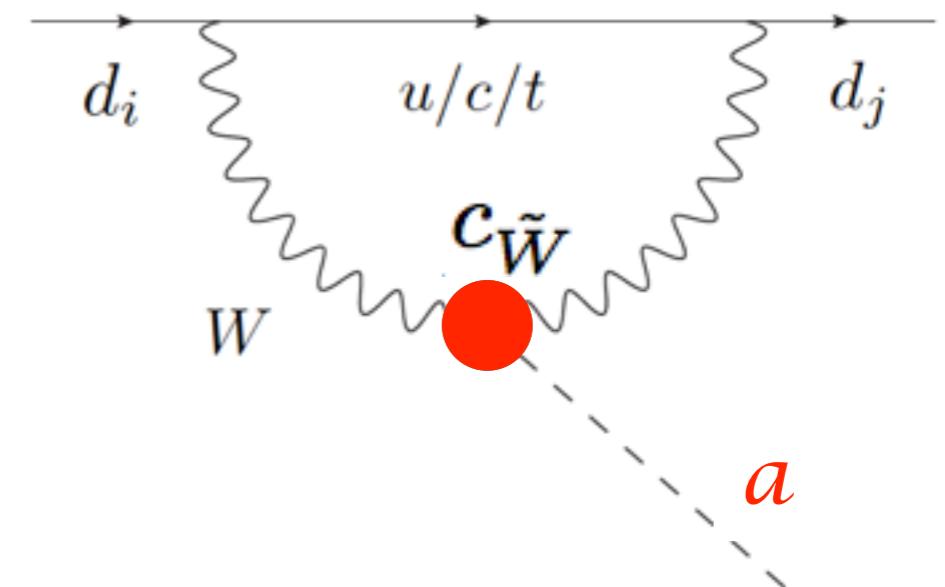
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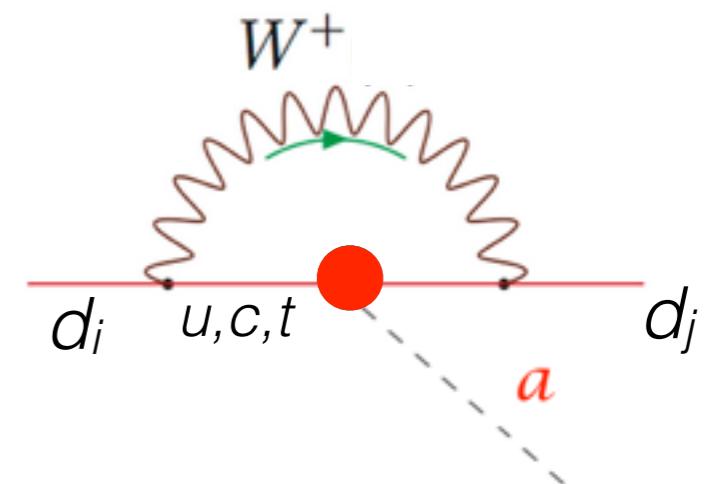


Izaguirre+Lin+Shuve 2016



But several ops. may contribute:

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



+Del Rey et al. in preparation

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

Higgs EFTs

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

II
SM EFT

Higgs EFTs

Linear
II
SM EFT

or Chiral

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

\mathbf{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:

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

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

h may not be an exact $SU(2)_L$ doublet

Longitudinal W,Z

Higgs EFTs

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in chiral:

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

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

Typical of “composite Higgs” models

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

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

Longitudinal W,Z

Higgs EFTs

Linear

or

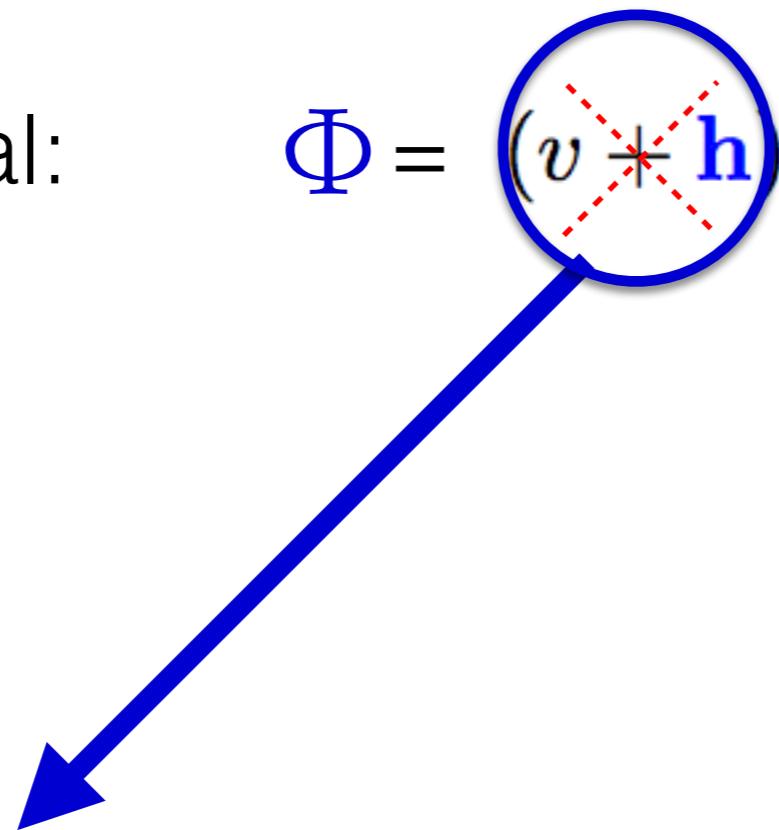
Chiral (non-linear)

in chiral:

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

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

Longitudinal W,Z



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

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

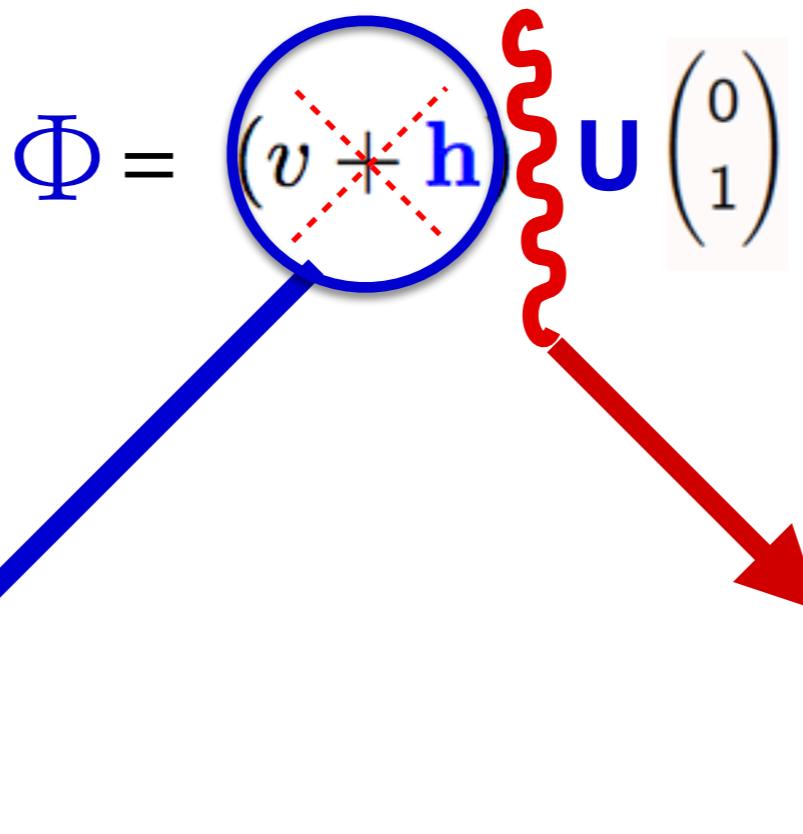
Higgs EFTs

Linear

or

Chiral (non-linear)

in chiral:



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

Longitudinal W,Z

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

independent !

some couplings decorrelate:
more operators at given order

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

Higgs EFTs

Linear or

Chiral (non-linear)

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

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)

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

Higgs EFTs

Linear or

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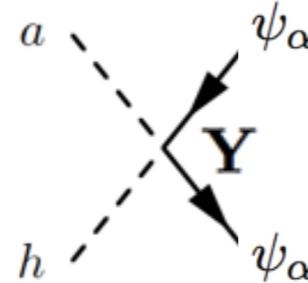
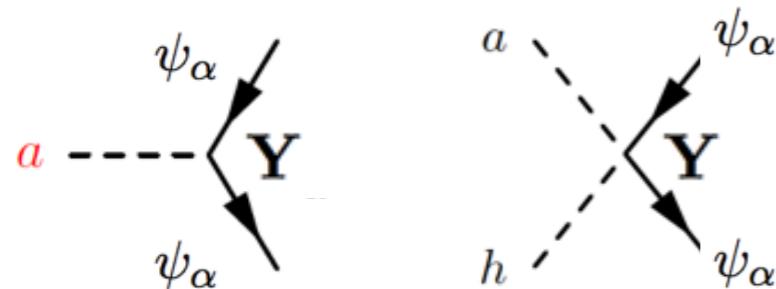
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$$\mathcal{A}_{2D}(h) = iv^2 \frac{\partial^\mu a}{f_a} \text{Tr}[\mathbf{T} \mathbf{V}_\mu] \mathcal{F}_{2D}(h)$$

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



as in the linear case

Higgs EFTs

Linear or

Chiral (non-linear)

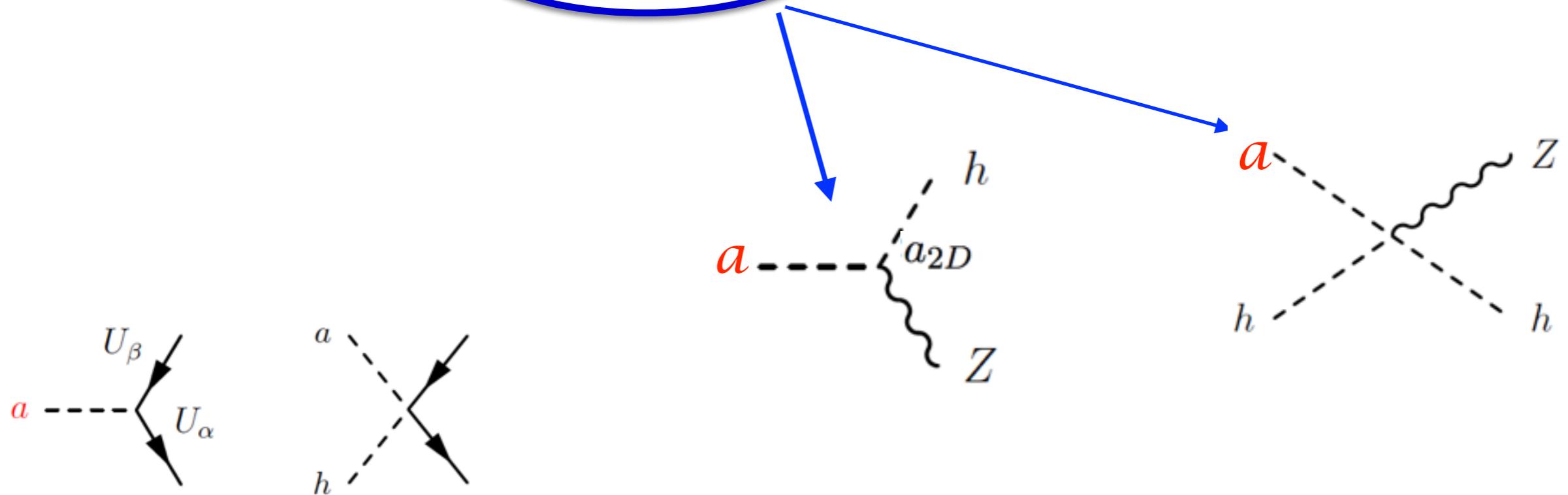
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$$ig Z_\mu \partial^\mu a \left(1 - 2a_{2D} \frac{h}{v} + b_{2D} \frac{h^2}{v^2} \right)$$

ALP-Higgs couplings survive !!
(unlike linear case)



as in the linear case

Higgs EFTs

Linear or

Chiral (non-linear)

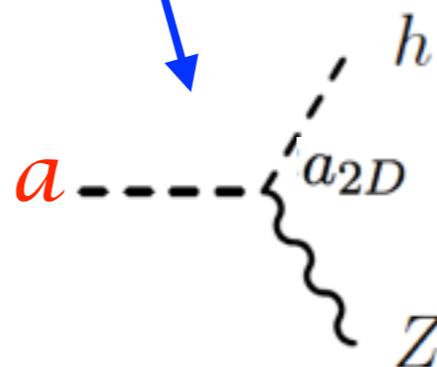
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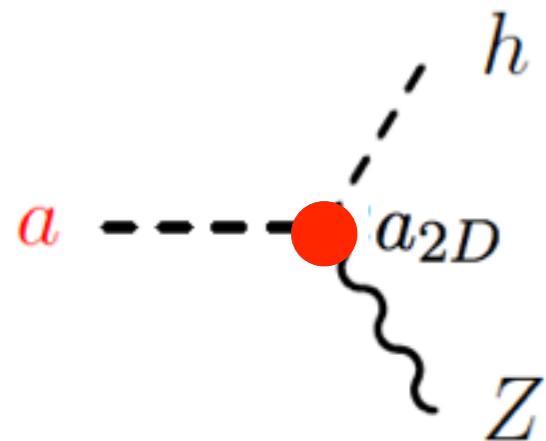
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ALP-Higgs couplings survive !!
(unlike linear case)



→ **New additional signals: mono-h, BSM Higgs decays**

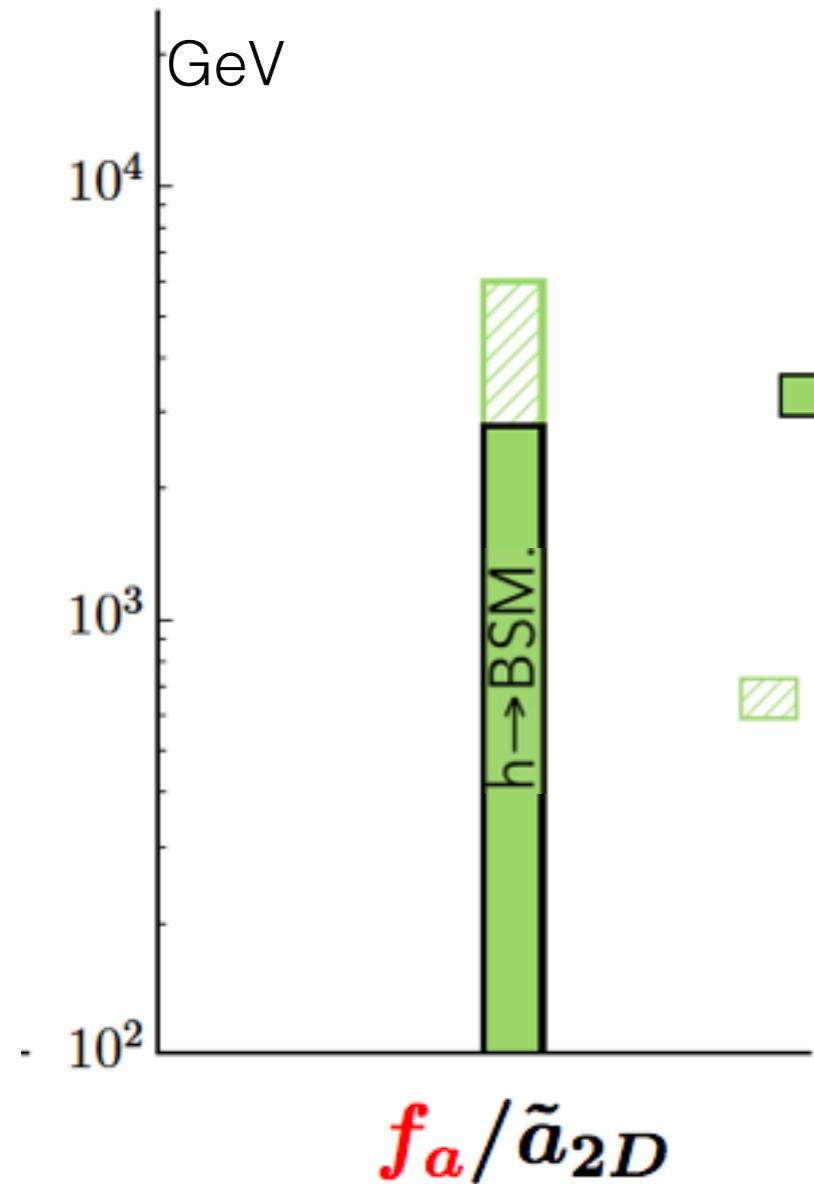
Non-standard Higgs decays



$$\Gamma_{\text{BSM}} = \Gamma_{\mathbf{h} \rightarrow \mathbf{a}Z} + \Gamma_{\mathbf{h} \rightarrow \mathbf{a}Z\gamma} + \Gamma_{\mathbf{h} \rightarrow \mathbf{a}f\bar{f}}$$

$$\text{Br}(h \rightarrow \text{BSM}) = \frac{\Gamma_{\text{BSM}}}{\Gamma_{\text{BSM}} + \Gamma_{\text{SM}}} \leq 0.34 \quad (95\% \text{ C.L.})$$

ATLAS and CMS
7 and 8 TeV

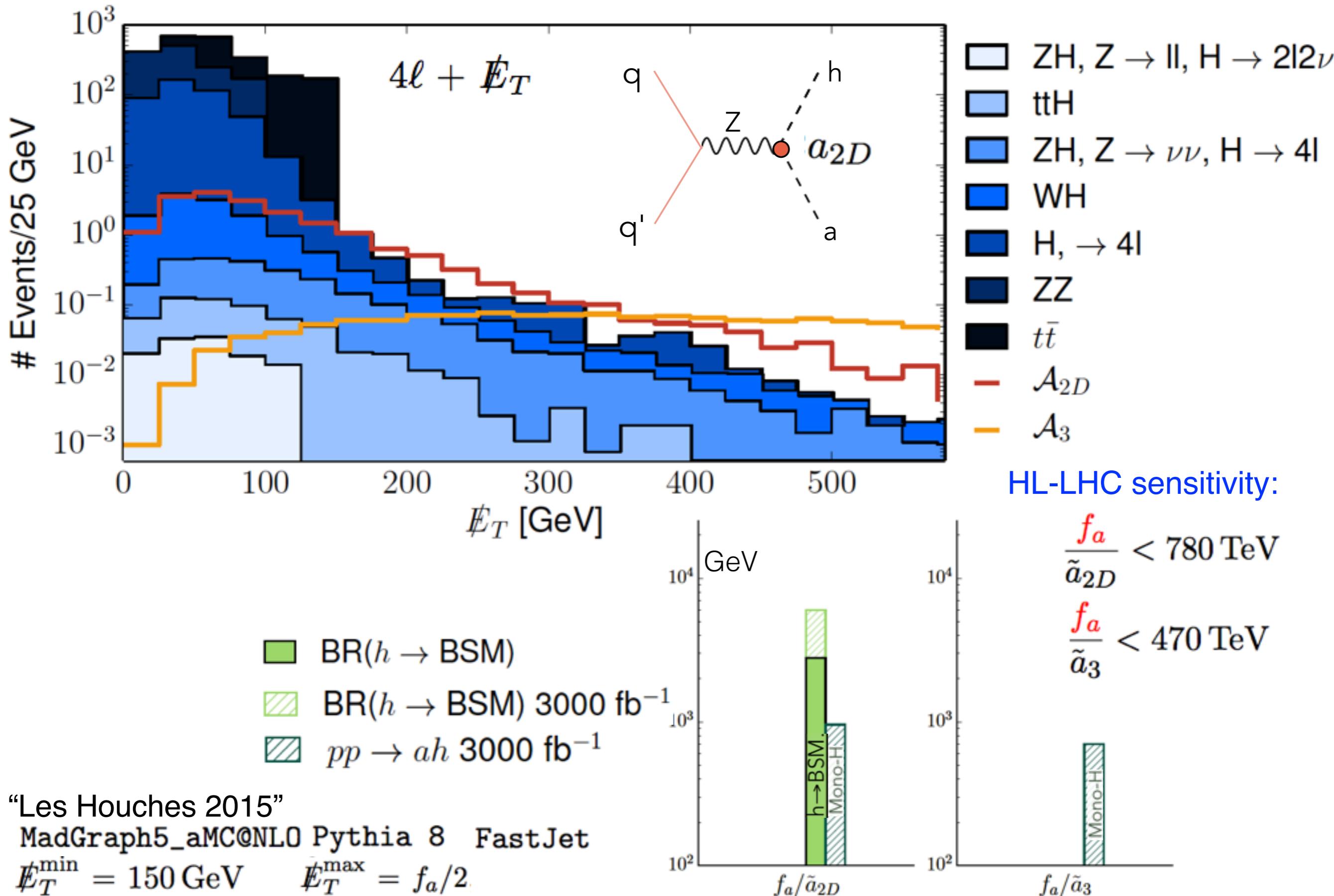


$$\frac{f_a}{\tilde{a}_{2D}} \gtrsim 2.78 \text{ TeV}$$

$$\frac{f_a}{\tilde{a}_{2D}} \gtrsim 6 \text{ TeV}$$

for $m_a \lesssim 34 \text{ GeV}$

Mono-Higgs : $pp \rightarrow a h$



Higgs EFTs

Linear or

Chiral (non-linear)

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

NLO, bosonic custodial preserving:

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

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

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

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

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

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

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

NLO bosonic, custodial breaking:

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

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

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

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

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

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

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

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

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

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

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

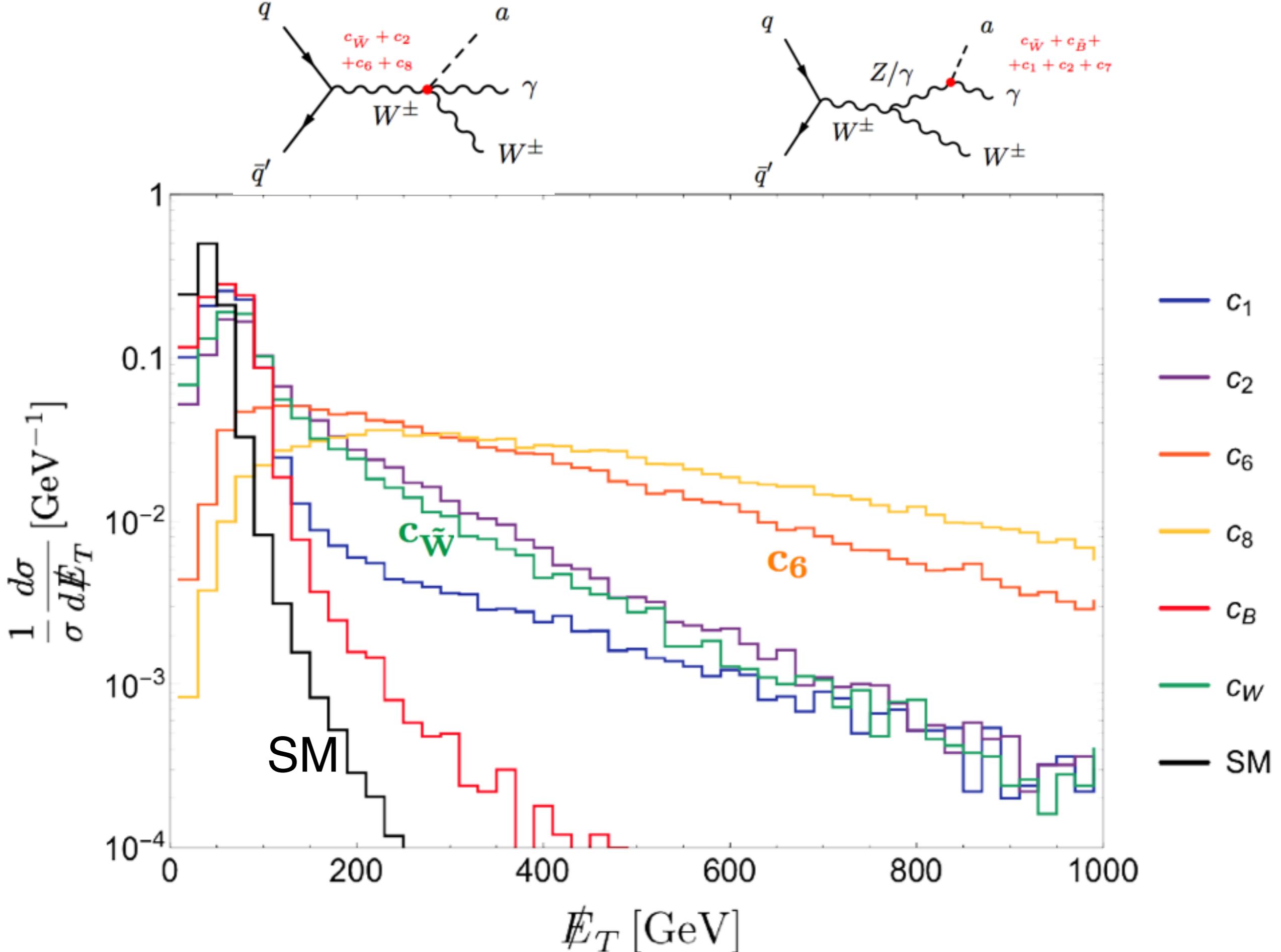
$$\mathcal{A}_{15}(h) = \frac{i}{(4\pi)^2} \text{Tr}[\mathbf{T} \mathbf{V}_\mu] \frac{\partial^\mu a}{f_a} \partial_\nu \mathcal{F}_{15}(h) \partial^\nu \mathcal{F}'_{15}(h)$$

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

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

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

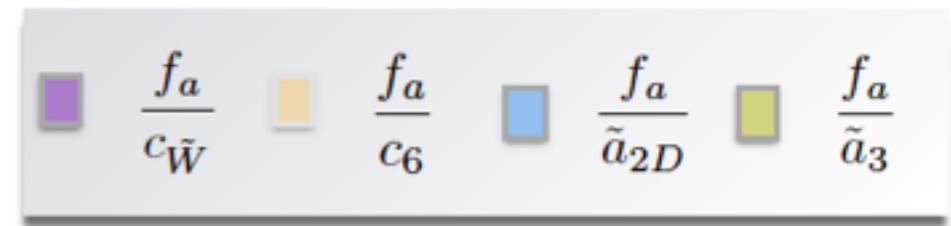
Associated production $pp \rightarrow \alpha W\gamma$



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

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

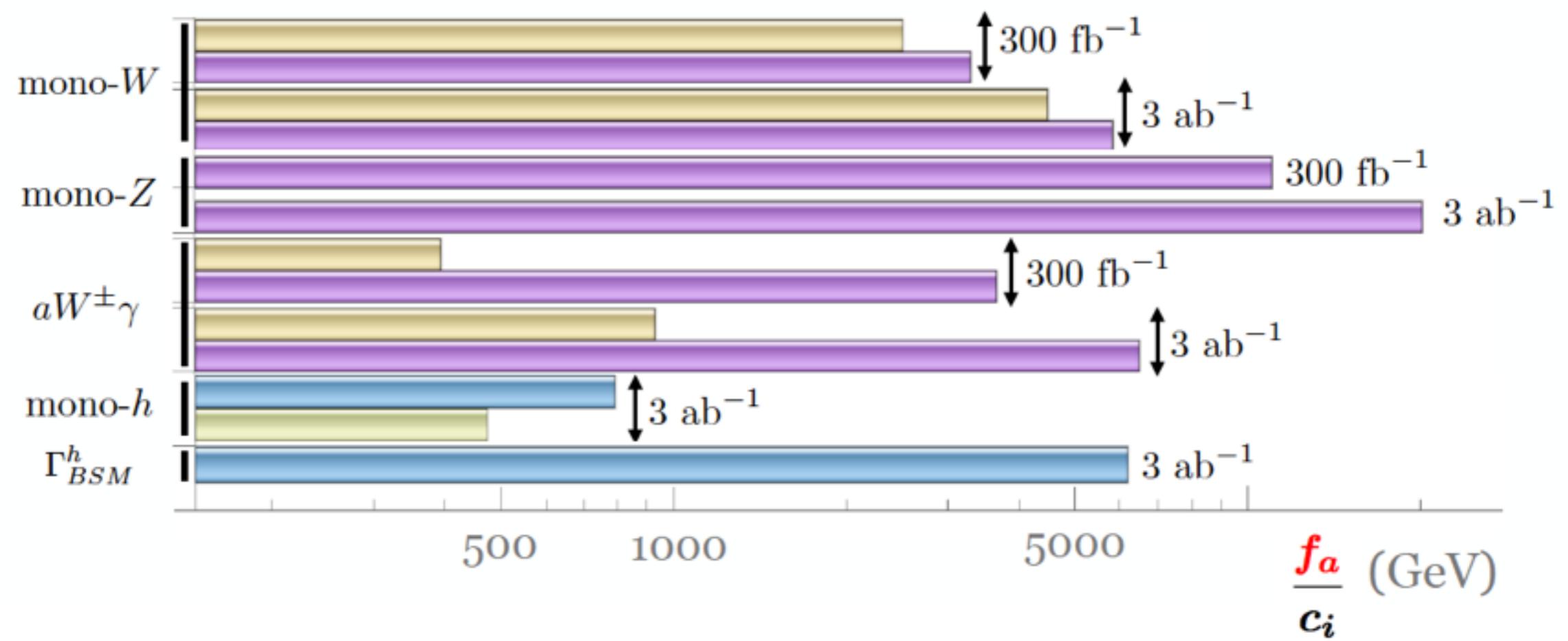
ALPs: collider constraints



Current limits



Prospects HL-LHC



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 —> mono- γ , -W/Z, -h, $\Gamma_{\text{BSM}}(h)$, etc. besides rare decays

Fish for them in your data!

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

Backup

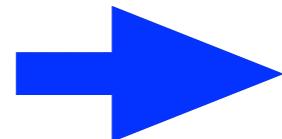
Validity of the EFT

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

For each given f_a , validity conditions:

- $m_T^{\max} < f_a$ for mono- W s, because the ATLAS search uses m_T as discriminating variable;
 m_T^{\max} denotes the highest m_T data bin.
- $2\cancel{E}_T^{\max} < f_a$ for the rest of accelerator signals, where \cancel{E}_T^{\max} denotes the highest \cancel{E}_T data bin.

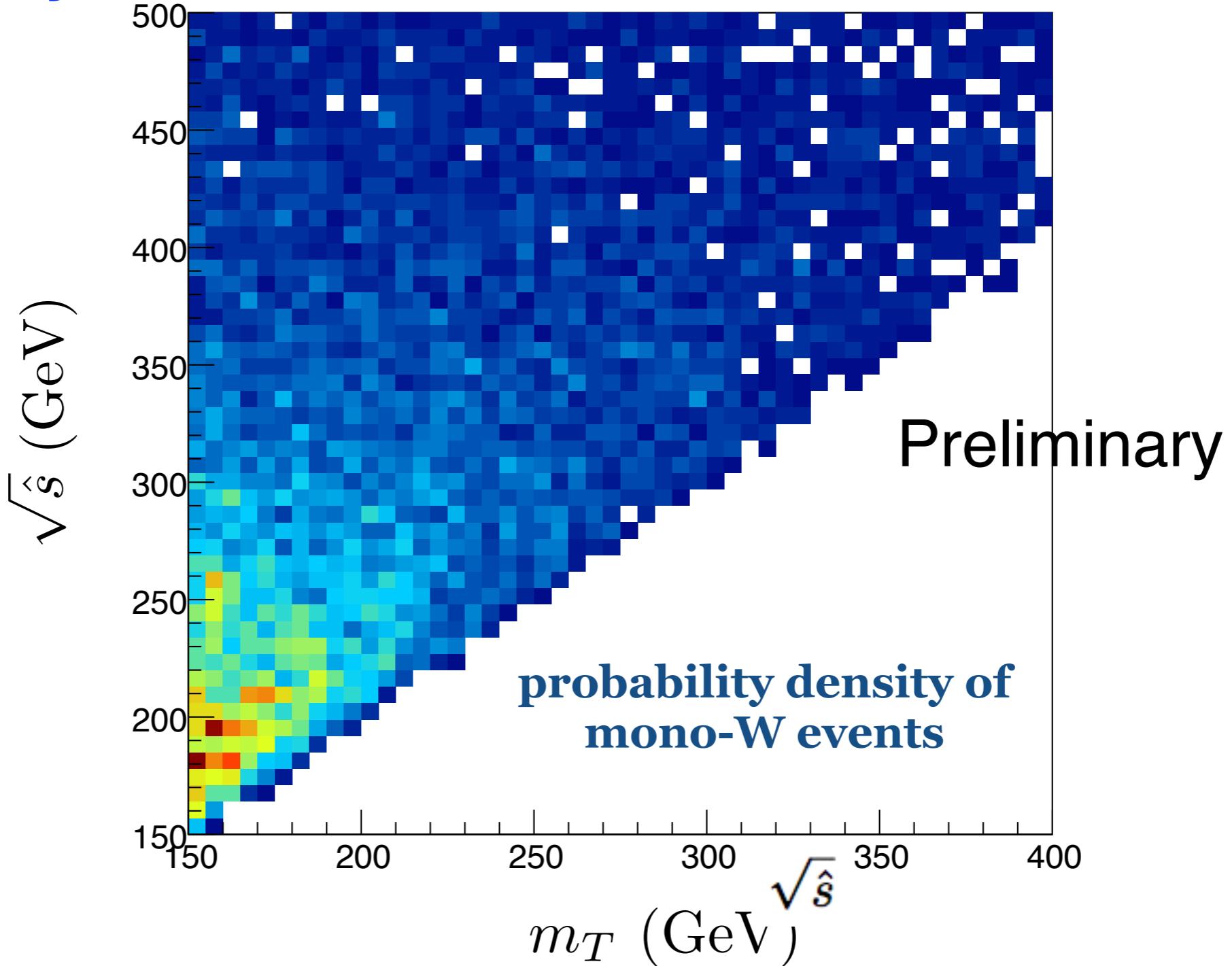
e.g. In mono- Z analysis with 2.3 fb^{-1} , the \cancel{E}_T value for the highest bin considered is 1.2 TeV

 That analysis valid for scales $f_a > 2.4 \text{ TeV}$.

Is this safe, give the fact that $m_{inv.} \geq m_T, \cancel{E}_T$?

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 $m_a = 1\text{MeV}$

$a \rightarrow \nu \bar{\nu} \nu \bar{\nu}$ It would simply become part of the \cancel{E}_T contributions

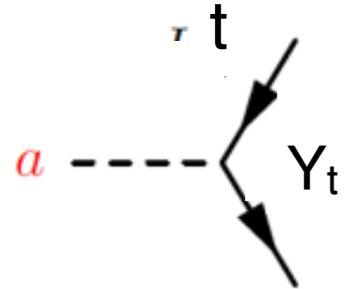
$a \rightarrow \gamma \gamma$ The distance d covered in the laboratory frame before decaying

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

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

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

Final state radiation off a top



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

Compare with susy searches of ttbar+2 neutralinos

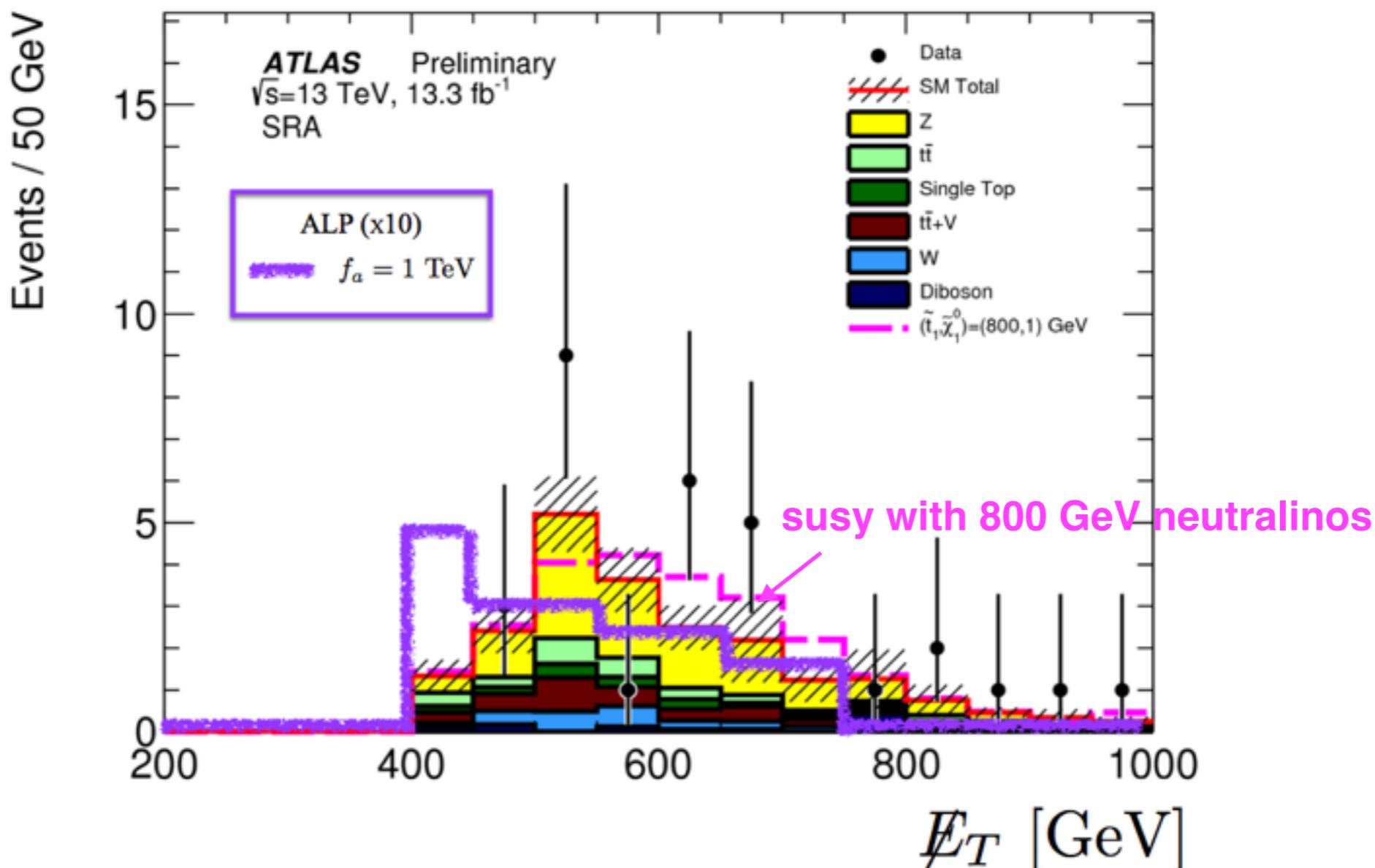


Figure 13: Missing energy distribution for the production of an light ALP in association with $t\bar{t}$ for 13.3 fb^{-1} of 13 TeV data. The normalization has been chosen with $f_a = 1 \text{ TeV}$ and then multiplied by a factor 10. We show the corresponding simulation of supersymmetric scenarios by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

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

ℓ	$c_{\tilde{W}}$ (mono- W)		$c_{\tilde{W}}$ (mono- Z)	
	e	μ	e	μ
$(f_a/c_{\tilde{W}})_{\min}$ [TeV]	1.28	1.65	3.77	2.54
$(f_a/c_{\tilde{W}})_{\min}$ [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 $A_{\tilde{W}}$ 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 Sust.].

Prospects on cW from mono-Z

ℓ	$c_{\tilde{W}}$ (mono- Z)			
	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. $\times 1/2$]	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 $\mathcal{L} = 300 \text{ fb}^{-1}$ and $\mathcal{L} = 3000 \text{ fb}^{-1}$ 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

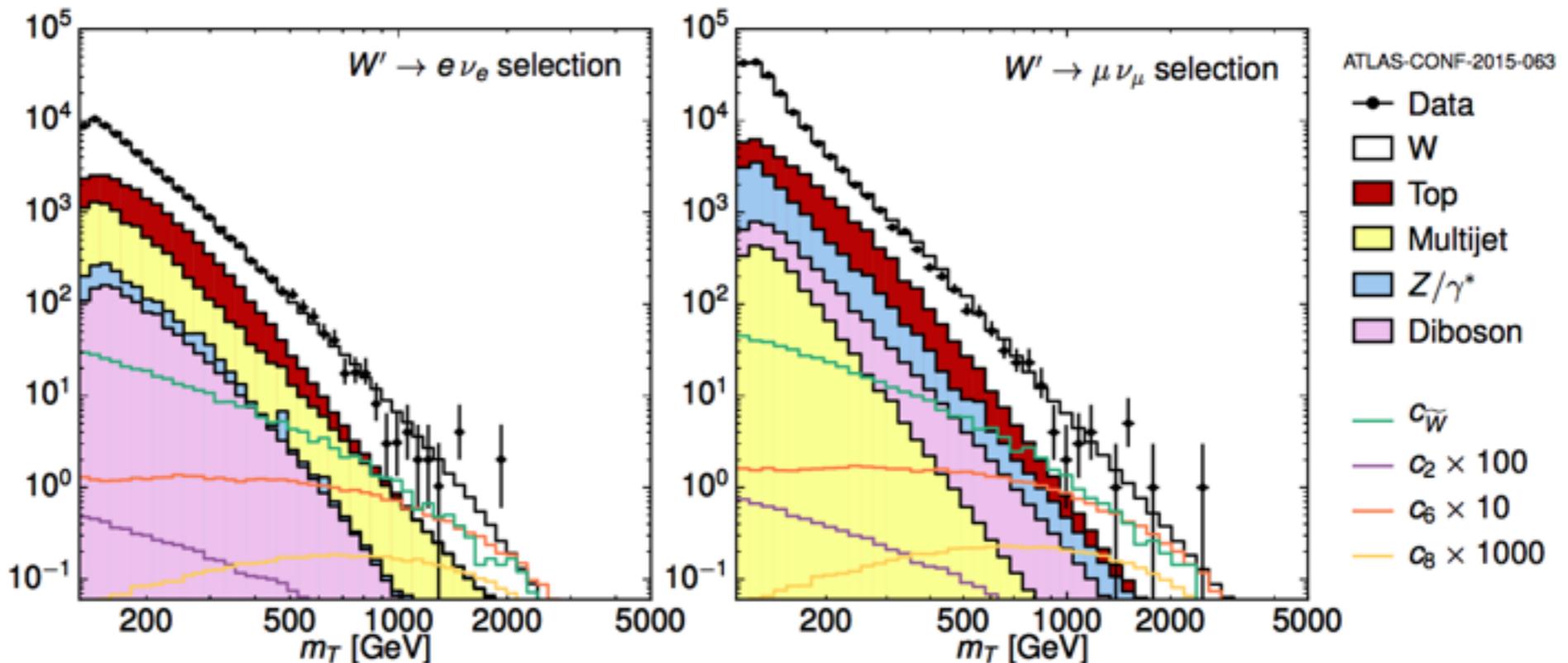
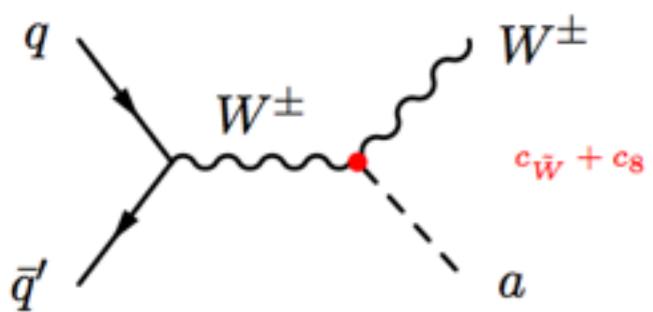


Figure 3: Transverse mass m_T distribution for aW^\pm ($W^\pm \rightarrow \ell^\pm \nu_\ell$) production in the $e + \cancel{E}_T$ final state (Left) and $\mu + \cancel{E}_T$ final state (Right), generated from $\mathcal{A}_{\tilde{W}}$ (green), \mathcal{A}_2 (purple), \mathcal{A}_6 (orange) and \mathcal{A}_8 (yellow). Also shown are the binned experimental data and dominant backgrounds from the 13 TeV (3.3 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. $\times 1/2$]	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 $aW\gamma$

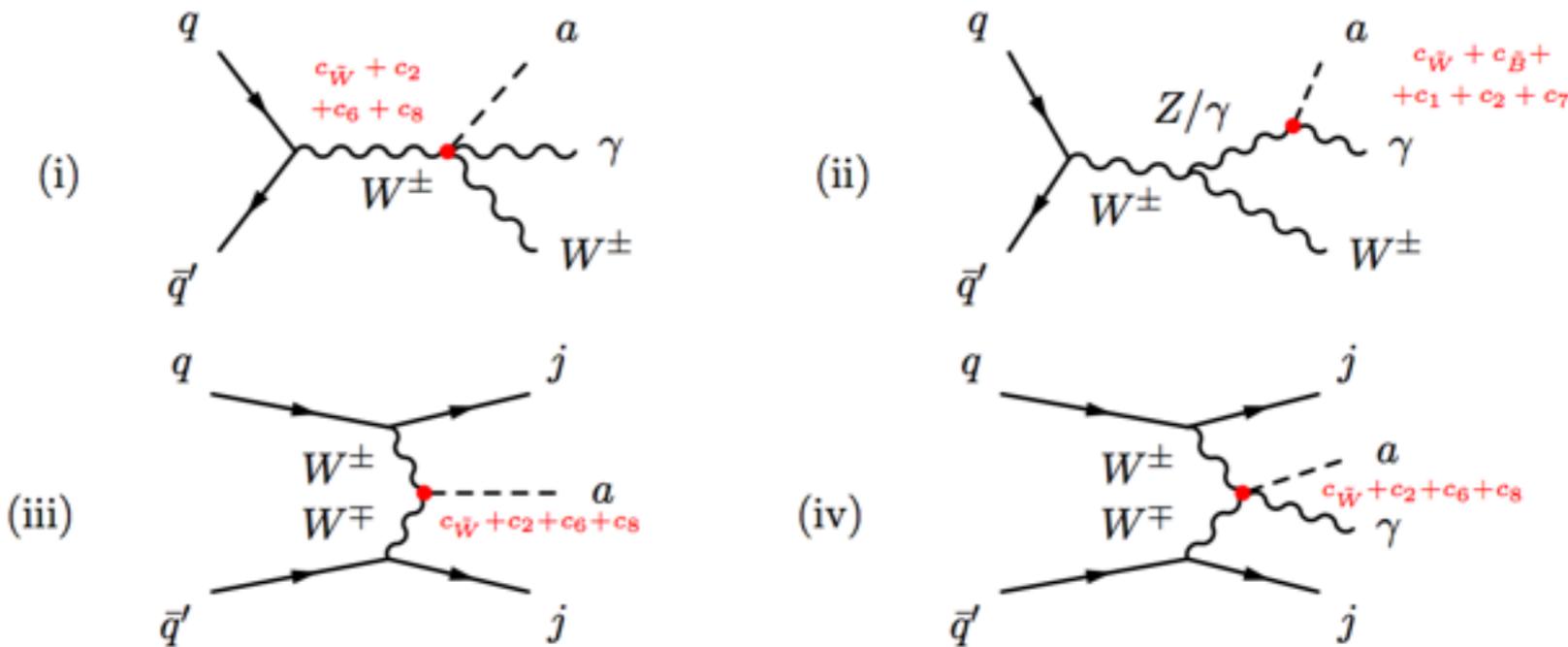


Figure 5: Main diagrams contributing to the processes analysed in Sect. 7.2. Upper line: $a\gamma W$ associated production. Lower line: VBF-type interaction producing ajj (iii) and $ajj\gamma$ (iv). The proportionality of each diagram to the non-linear parameters is indicated in the figure (overall factors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

	c_6	$c_{\tilde{W}}$
Luminosity [fb^{-1}]	300 3000	300 3000
Optimal \cancel{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 \cancel{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 $aW\gamma$

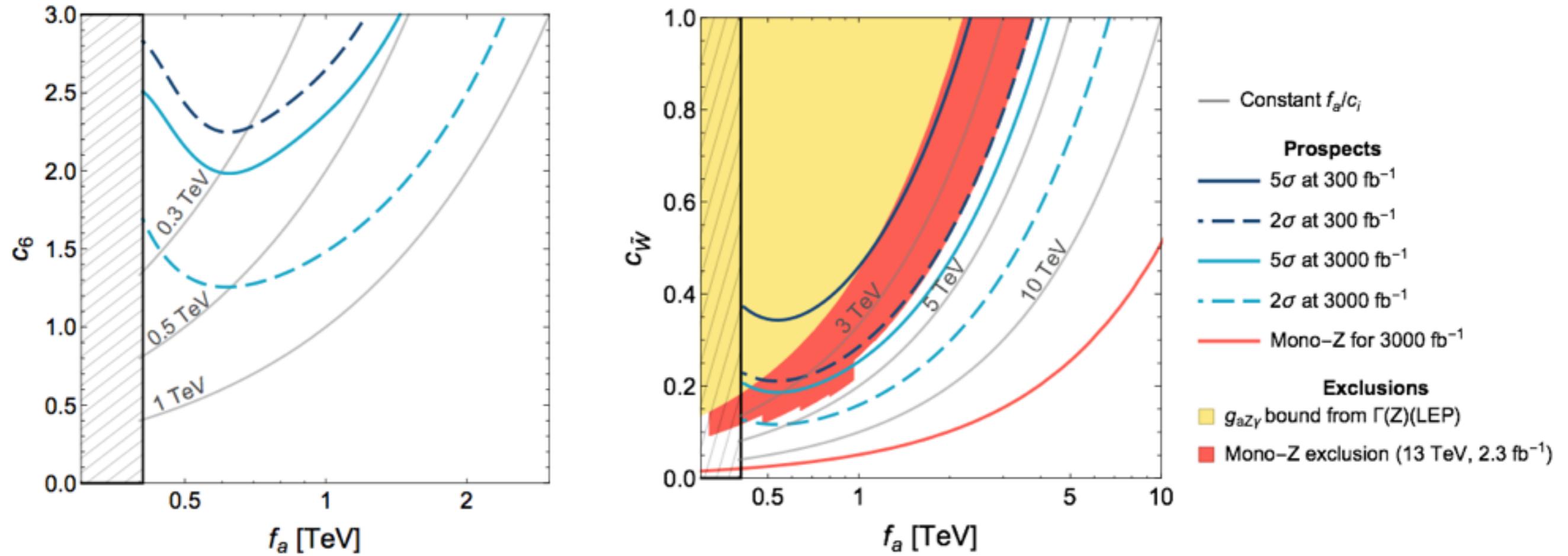


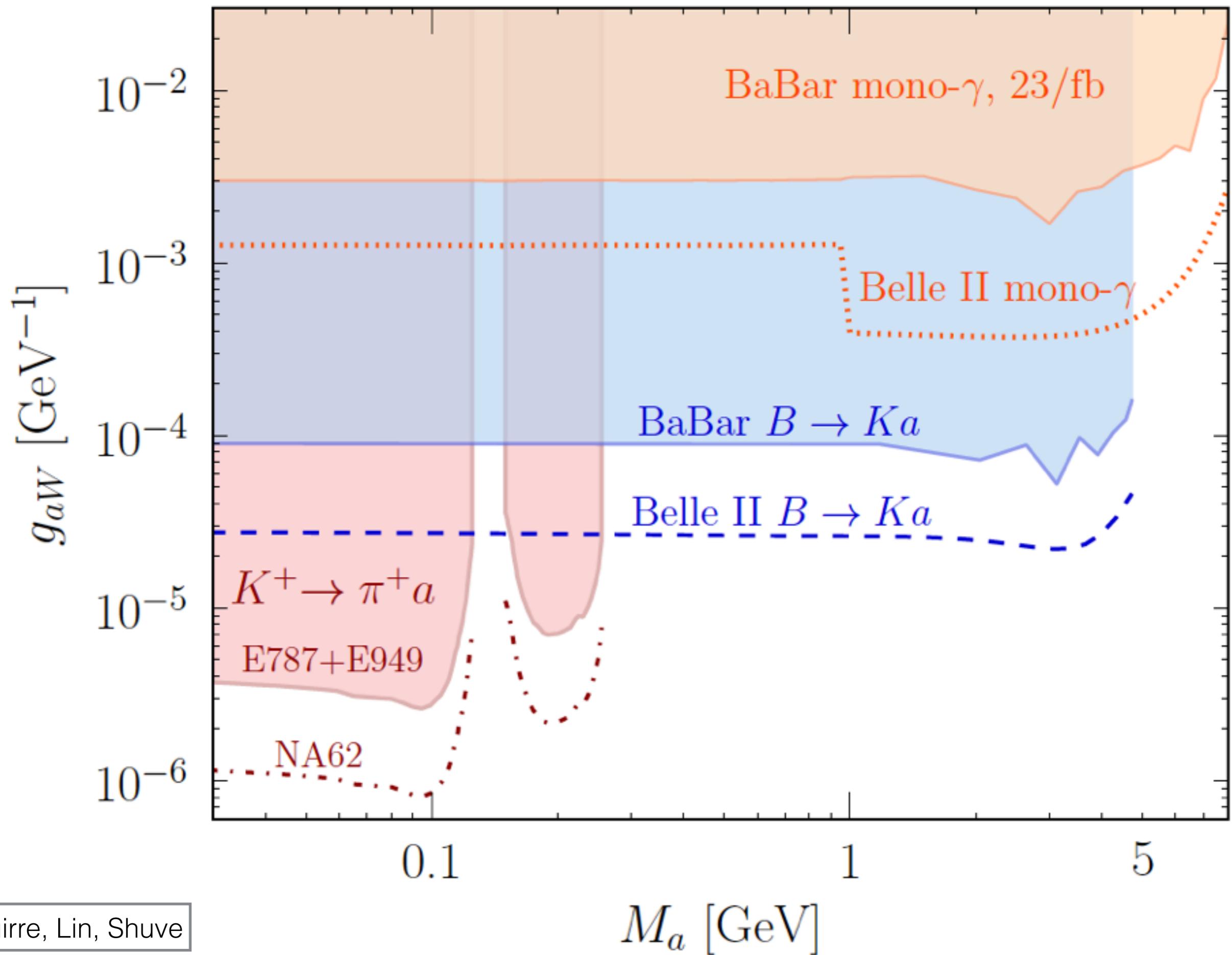
Figure 8: Contours for $\sigma = 2$ (dashed) and $\sigma = 5$ (solid) sensitivity to $pp \rightarrow aW^\pm\gamma$ ($W^\pm \rightarrow \ell^\pm\nu$) signal at the LHC with $\sqrt{s} = 13$ TeV and for an integrated luminosity of 300 fb^{-1} (dark blue) and 3000 fb^{-1} (light blue), as a function of $\{f_a, c_i\}$. 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 $f_a < 2\cancel{E}_T^{\min}$, 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 $\sqrt{s} = 13$ TeV LHC with 2.3 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.: $W\gamma$, measured in LHC 7TeV. scaled here by 20% to account for subdominant backs.

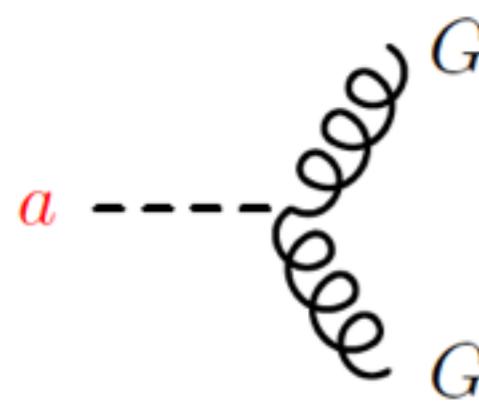
Parton level analysis. $p_T^\gamma > 20 \text{ GeV}$, $p_T^\ell > 20 \text{ GeV}$, $|\eta^\gamma| < 2.5$ and $|\eta^\ell| < 2.5$

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

$a \rightarrow \text{invisible}$



Present bounds on gluon-ALP couplings



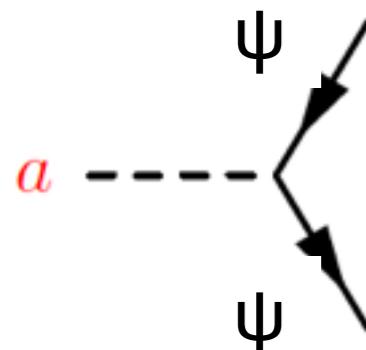
$$\mathcal{A}_{\tilde{G}} = -G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \frac{a}{f_a}$$

$$\frac{c_{\tilde{G}}}{f_a} \lesssim 2.5 \cdot 10^{-5} \text{ GeV}^{-1} \quad (\text{95\% C.L.}) \quad \text{for} \quad m_a \lesssim 0.1 \text{ GeV}$$

Mimasu+Sanz recasting ATLAS and CMS bounds

in addition to K \rightarrow π , SN, etc...

Present bounds on fermion-Alp couplings



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

Beam Dump:

(Dolan et al. 2014)

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

XENON100:

(Aprile et al. 2014)

$$g_{ae}/f_a < 1.5 \cdot 10^{-8} \text{ GeV}^{-1}$$

$$m_a < 1 \text{ keV}$$

Red Giants:

(Viaux et al. 2013)

$$g_{ae}/f_a < 8.6 \cdot 10^{-10} \text{ GeV}^{-1}$$

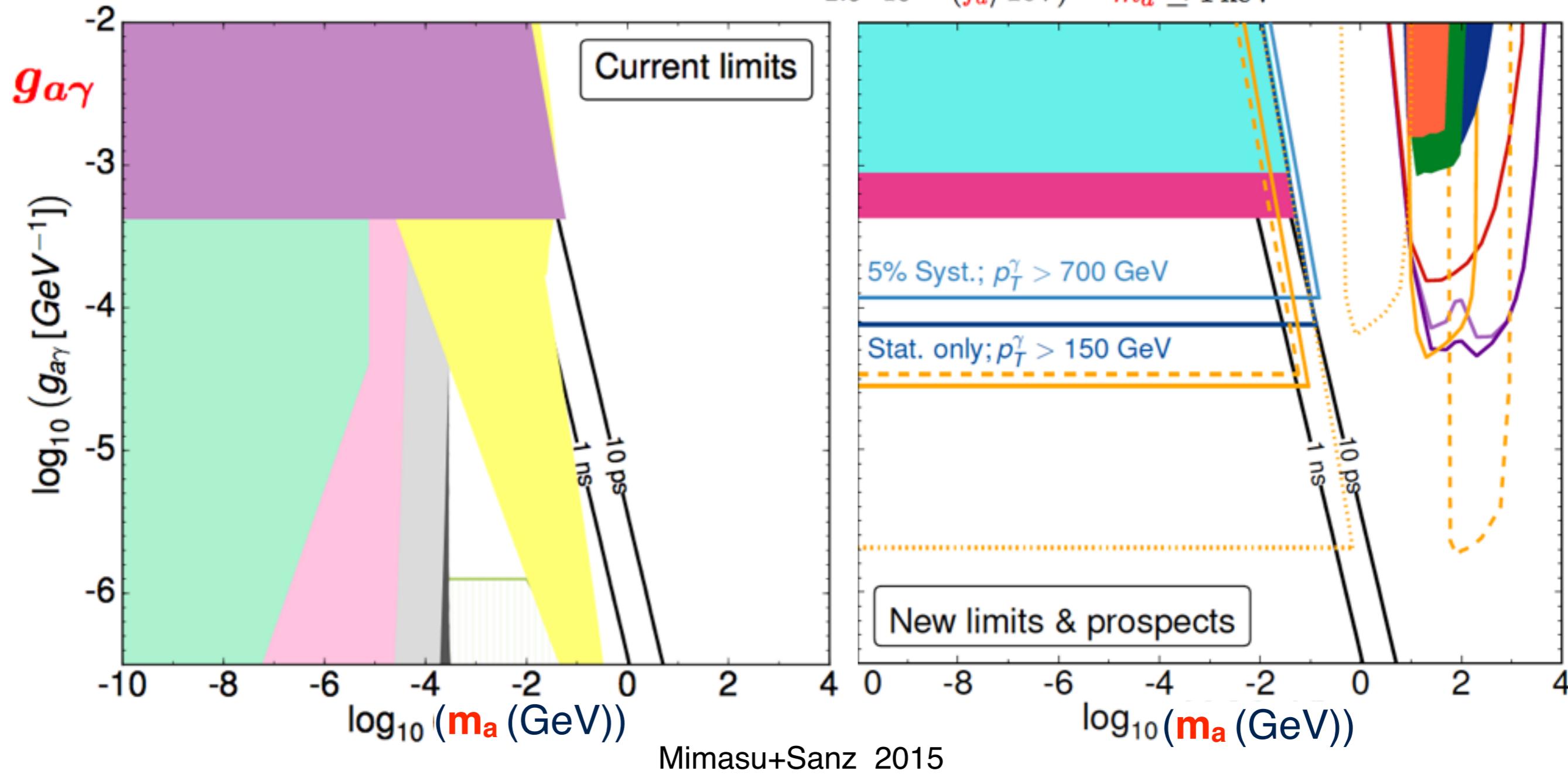
$$m_a \lesssim \text{eV}$$

Bounds on photon-ALP coupling

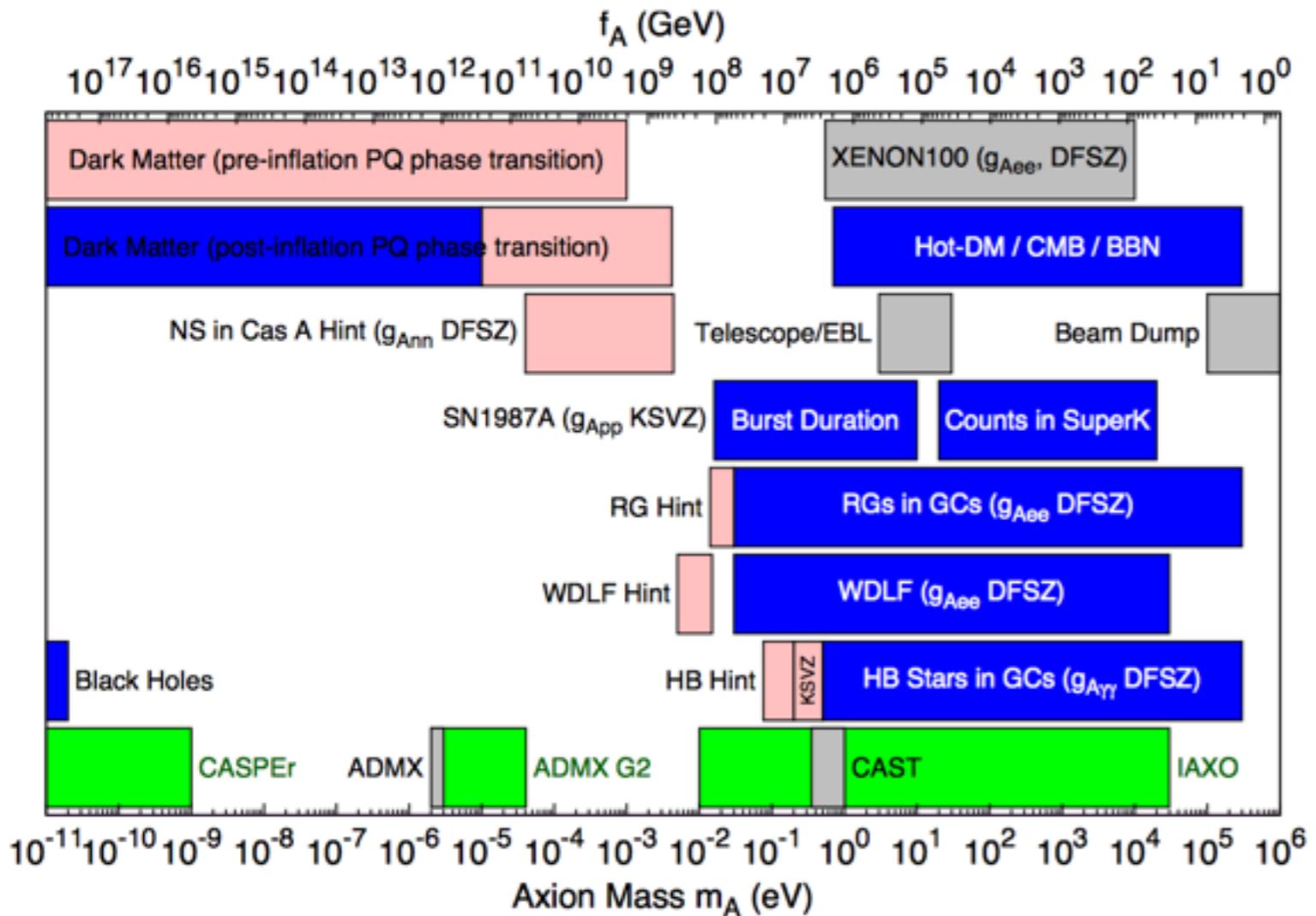
e.g. 90% CL: $|c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2| \lesssim$

$$0.0025 \text{ (} f_a/\text{TeV}) \quad m_a \leq 1 \text{ MeV}$$

$$2.5 \cdot 10^{-8} \text{ (} f_a/\text{TeV}) \quad m_a \leq 1 \text{ keV}$$



Other Bounds	Collider Bounds	Future Reach
CAST	LHC @ 7 TeV: mono- γ , 5 fb^{-1}	ILC @ 240 GeV, 1 ab^{-1}
Beam dump	LHC @ 8 TeV: mono- γ , 19.6 fb^{-1}	TLEP @ 1 TeV, 10 ab^{-1}
Solar ν flux	LEP @ M_Z : tri- γ , 66 pb^{-1}	Belle II @ 10.6 GeV, 50 ab^{-1}
Horizontal Branch	LEP @ 189 GeV: tri- γ , 153 pb^{-1}	LHC @ 13 TeV: mono- γ , 3 ab^{-1}
BBN	CDF: 3- γ , 1.2 fb^{-1}	LHC @ 13 TeV: tri- γ , 3 ab^{-1}
Supernova 1987a	LEP: mono- γ	LHC @ 8 TeV: tri- γ , 19.6 fb^{-1}



exclusion ranges as described in the top section. The intervals in the bottom row are the approximate search ranges for standard or variant axions. The 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 $\cos^2 \beta' = 1/2$.