Axion-Like-Particles EFT
&
collider signals

Ilaria Brivio

Niels Bohr Institute, Copenhagen

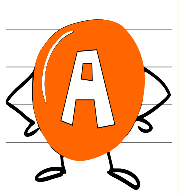
based on 1701.05379 in collaboration with
B. Gavela, L. Merlo, K. Mimasu, J.M. No, R. del Rey, V. Sanz

The Niels Bohr International Academy

VILLUM FONDEN

centre for particle physics Discovery

Axion-Like-Particles: identikit



NAME: **ALP** [Axion-Like Particle]

DESCRIPTION: pseudo-scalar (CP odd)

free characteristic scale f_a

SPECIAL MARKS: only derivative interactions:
(approximate) **shift symmetry** $a(x) \to a(x) + c$

↓

can have a mass but $m_a \ll f_a$

Axion-Like-Particles: identikit

NAME: **ALP** [Axion-l

DESCRIPTION: pseudo-s

free cha

SPECIAL MARKS: only

(appr

from $U(1)_{PQ}$ dynamical **solution to the strong CP problem**

Peccei,Quinn PRL38 (1977) 1440

exact Goldstone

mass+potential from instantons

$m_a \sim 1/f_a \lesssim \text{eV}$ → narrow pheno window

can have a mass but $m_a \ll f_a$

POSSIBLE IDENTITIES: (invisible) QCD axion -- $m_a f_a \sim m_\pi f_\pi$

Axion-Like-Particles: identikit

NAME: **ALP** [Axion-Like Particle]

DESCRIPTI

SPECIAL M

recent development:

still **solves** strong CP problem

$+$

relax: $m_a \not\propto 1/f_a$

$\rightarrow$ heavier masses $+$ lower scales allowed

$\rightarrow$ easier to catch

Dimopoulos,Susskind 1979
Tye PRL47 (1981) 1035
Rubakov 9703409
Berezhiani,Gianfagna,Giannotti 0009290
Hook 1411.3325
Gerghetta,Nagata,Shifman 1604.01127
Chiang et al. 1602.07909
Kobakhidze 1607.06552
Dimopoulos et al 1606.03097

$x) + c$

POSSIBLE IDENTITIES: (invisible) QCD axion -- $m_a f_a \sim m_\pi f_\pi$

(visible) heavy QCD axion -- $m_a f_a \neq$ const.

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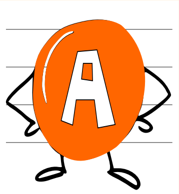

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Dark Matter

GB from string compactification

axiflavon Calibbi et al. 1612.08040

relaxion Graham,Kaplan,Rajendran 1504.07551

...

Looking for the ALP is an Effective way

General analysis: construct an **effective theory of SM + ALP**

$$\mathcal{L}_{\rm ALP} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{a-\rm SM}$$

Remember:

free characteristic scale f_a

only derivative interactions:
(approximate) **shift symmetry** $a(x) \to a(x) + c$

$\downarrow$

can have a mass but $m_a \ll f_a$

$\Downarrow$

interaction Lagrangian has the form

$$\mathcal{L}_{a-\rm SM} \sim (\rm SM)^\mu \frac{\partial_\mu a}{f_a}$$

Effective Field Theory for ALPs

A complete basis for the CP even, bosonic sector

Georgi,Kaplan,Randall PLB169 (1986) 73

$$\mathcal{L}_{a-\mathrm{SM}} = \sum_i C_i \mathcal{Q}_i$$

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

$$\mathcal{Q}_{\tilde{W}} = -W^I_{\mu\nu}\tilde{W}^{I\mu\nu}\frac{a}{f_a}$$

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

$$\mathcal{Q}_{aH} = i(H^\dagger \overleftrightarrow{D}^\mu H)\frac{\partial_\mu a}{f_a}$$

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$$\mathcal{Q}_{aH} = i(H^\dagger \overleftrightarrow{D}^\mu H)\frac{\partial_\mu a}{f_a}$$

invariant under $a(x) \to a(x) + c$

invariance **broken** at the quantum level (instanton effects)
but the operator is **relevant**
e.g. for QCD axion

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unitary gauge $\rightarrow \dfrac{v^2 g}{2c_\theta f_a} Z^\mu \partial_\mu a$

redefined via:

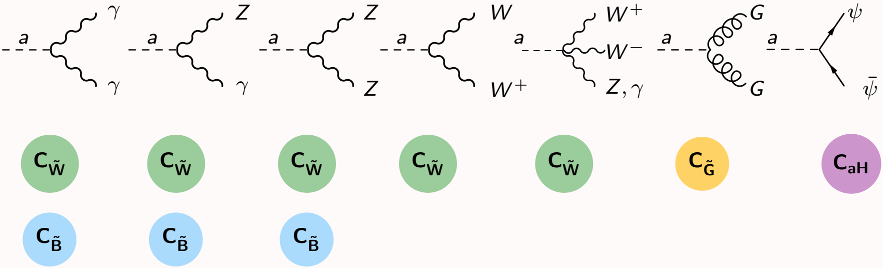
$H \rightarrow \exp\left(C_{aH}\dfrac{ia}{f_a}\right) H$

replaced by

$$\mathcal{Q}^\psi_{aH} = i\frac{a}{f_a}\left[\bar{q}Y_u\tilde{H}u - \bar{q}Y_d Hd - \ell Y_e He\right] + \text{h.c.}$$

EFT for ALPs – existing constraints

Relevant ALP couplings in the EFT



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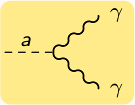
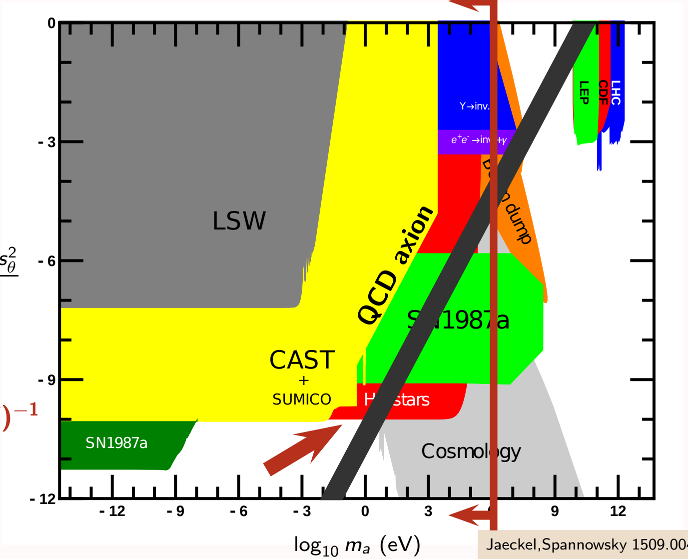


the most constrained

$$\log_{10}\frac{C_{\tilde{B}}c_\theta^2 + C_{\tilde{W}}s_\theta^2}{f_a}\quad [\mathrm{GeV}^{-1}]$$

$(10^7\ \mathrm{TeV})^{-1}$

our focus



Jaeckel,Spannowsky 1509.00476

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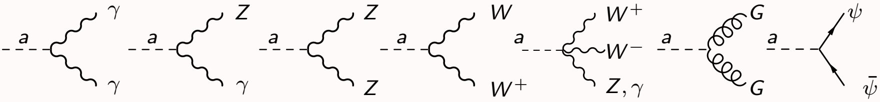

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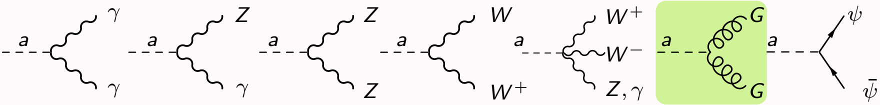

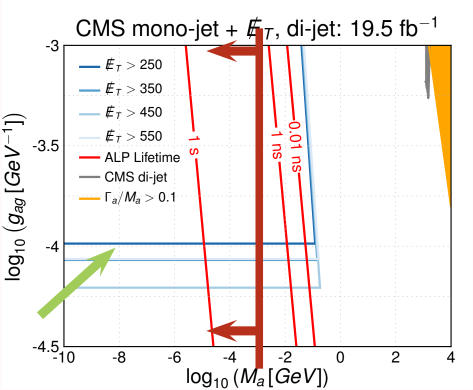

constrained e.g. from mono-jet

$$\frac{f_a}{C_{\tilde{G}}} \gtrsim 10 \text{ TeV}$$

Mimasu,Sanz 1409.4792

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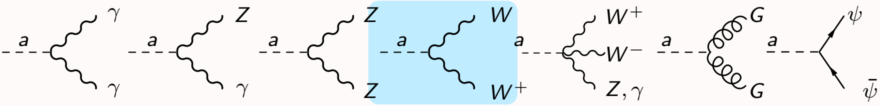
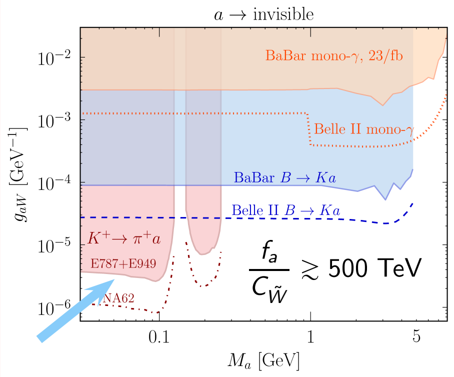
Relevant ALP couplings in the EFT

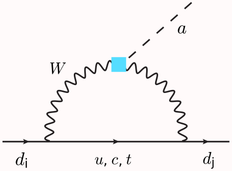




Izaguirre,Lin,Shuve 1611.09355

recent development:

constraints from
$B \to Ka$, $K \to \pi a \ldots$



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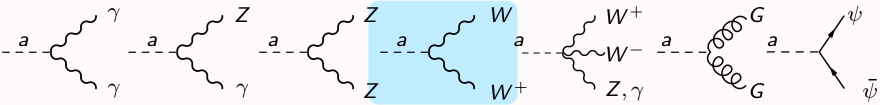
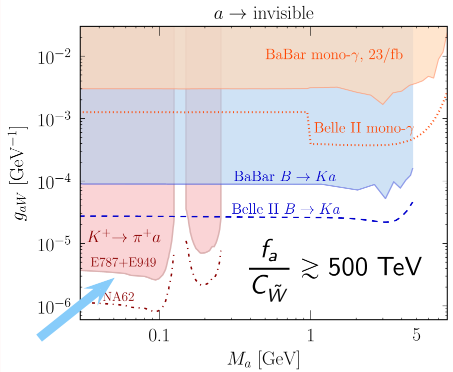




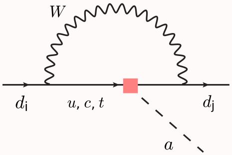
$$\frac{f_a}{C_{\tilde W}} \gtrsim 500\ \text{TeV}$$

Izaguirre,Lin,Shuve 1611.09355

recent development:

constraints from $B \to Ka$, $K \to \pi a \ldots$

!



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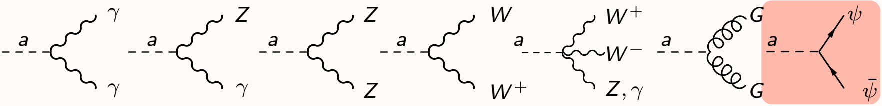


also from **rare meson decays**: $\frac{g_{a\psi}}{f_a} \lesssim 3.4 \cdot 10^{-8} - 2.9 \cdot 10^{-6}$ GeV^{-1}

Dolan et al. 1412.5174

for 1 MeV$\lesssim m_a \lesssim 3$ GeV

specifically to **e**

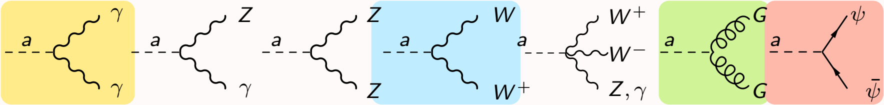
$m_a \lesssim 1$ keV $\quad \frac{g_{ae}}{f_a} \lesssim 1.5 \cdot 10^{-8}$ GeV^{-1} (Xenon) Xenon100 1404.1455

$m_a < 1$ eV $\quad \frac{g_{ae}}{f_a} \lesssim 8.6 \cdot 10^{-10}$ GeV^{-1} Viaux et al. 1311.1669

(high-precision photometry of red giants globular clusters)

EFT for ALPs – existing constraints

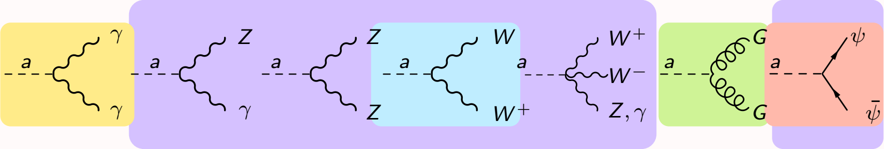
Relevant ALP couplings in the EFT



Other couplings have been largely disregarded

EFT for ALPs – extending the picture

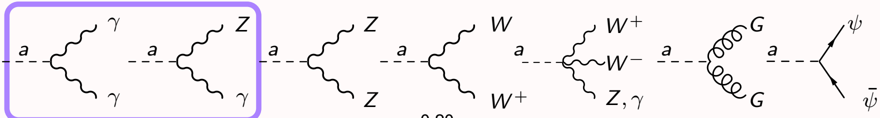
Two directions!



explore further **LHC constraints** to tackle more couplings

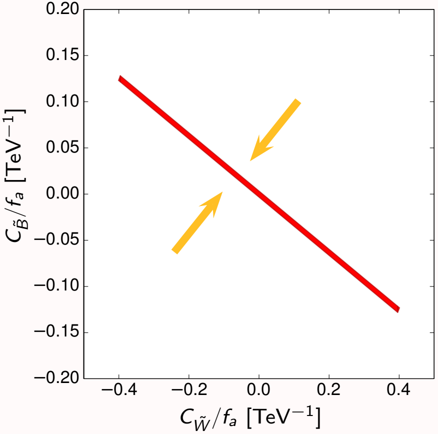
Remember
- looking for a pGB, $m_a \ll f_a$. for concreteness
  $\boldsymbol{m_a < 1}$ **MeV**
- assumed to be **stable** @ LHC → $\not{E}_T$ signature

Including further collider constraints



$a\gamma\gamma$ $\qquad \dfrac{C_{\tilde{B}} c_\theta^2 + C_{\tilde{W}} s_\theta^2}{f_a}$

$aZ\gamma$ $\qquad \dfrac{4 s_{2\theta}(C_{\tilde{W}} - C_{\tilde{B}})}{f_a}$



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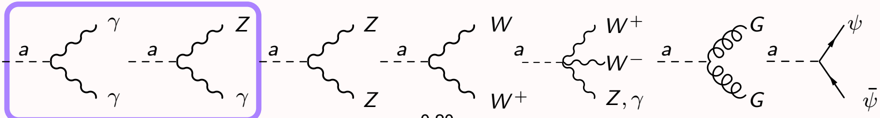

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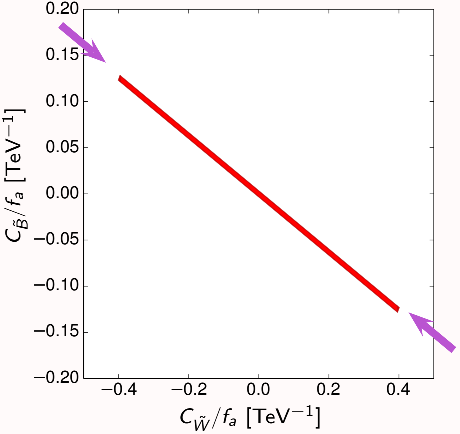
$aZ\gamma$ $\quad \dfrac{4 s_{2\theta}(C_{\tilde W} - C_{\tilde B})}{f_a}$

$\Gamma(Z \to a\gamma) < \Gamma(Z \to \text{BSM}) < 2\ \text{MeV}$



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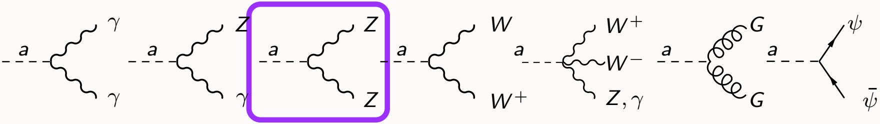
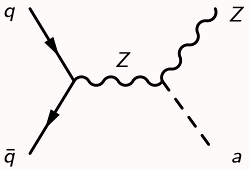


mono-Z

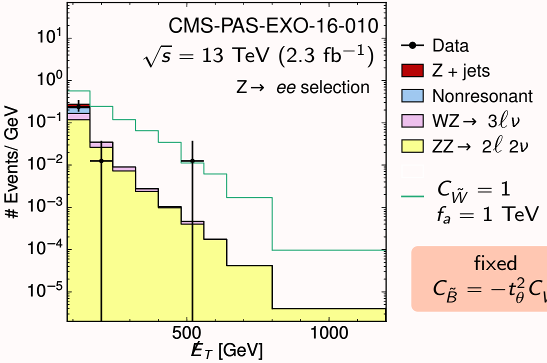


$$\frac{f_a}{C_{\tilde{W}}} \gtrsim 3.8 \text{ TeV}$$

projection HL-LHC:

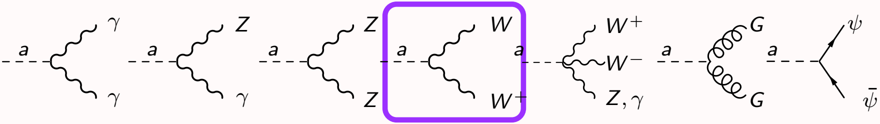
16 – 21 TeV

(depending on syst.)

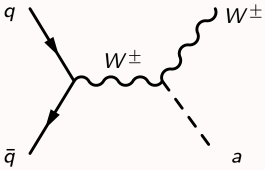


fixed
$C_{\tilde{B}} = -t_\theta^2 C_{\tilde{W}}$

Including further collider constraints



mono-W

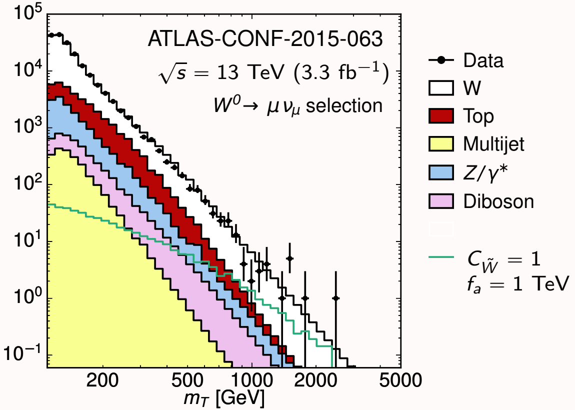


$$\frac{f_a}{C_{\tilde W}} \gtrsim \mathbf{1.7}\ \text{TeV}$$

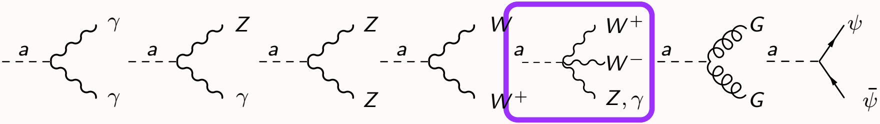
projection HL-LHC:

2 – 6 TeV

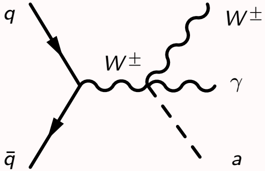
(depending on syst.)

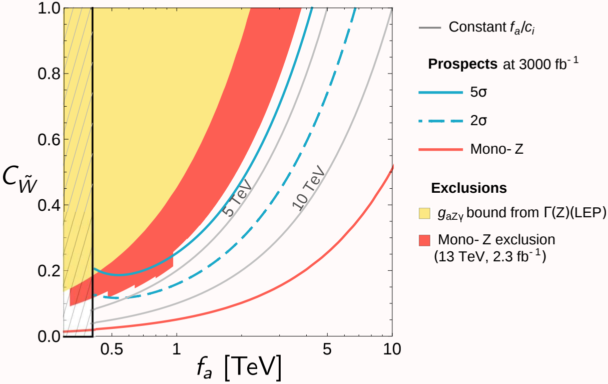


Including further collider constraints



aWγ prod.

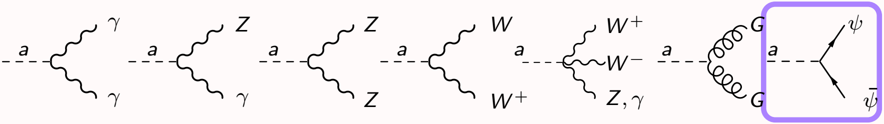




projection HL-LHC:

$$\frac{f_a}{C_{\tilde W}} \gtrsim 6.8 \text{ TeV}$$

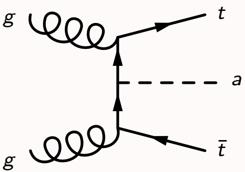
Including further collider constraints



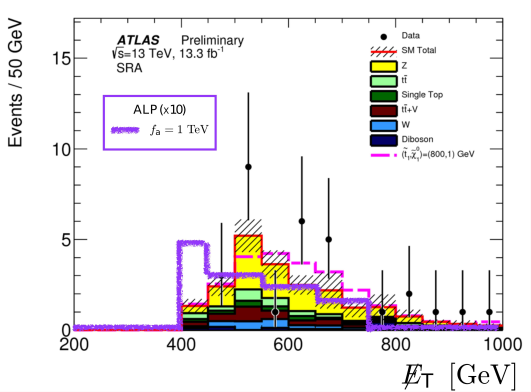
a proposal:

t$\bar{t}$a prod.

(neutralino searches)

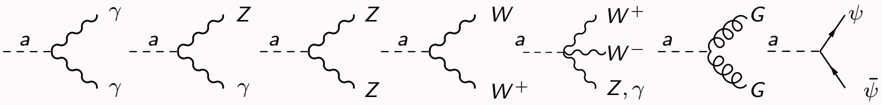


to constrain $\dfrac{Y_t C_{aH}}{f_a}$



EFT for ALPs – extending the picture

Two directions!



explore further **LHC constraints** to tackle more couplings

what happens if the Higgs is **not in a doublet**?

(how does a HEFTy ALP look like?)

Non-linear EFT

The doublet structure of the Higgs is not necessary for EWSB
(required only for exact unitarization)

relaxing this assumption $\longrightarrow$ **non-linear EFT** (a.k.a. chiral EFT, HEFT)

Appelquist,Bernard (1980)
Longhitano (1981)

$$H = \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

independent

h

treated as a singlet
with arbitrary couplings

$$\mathcal{F}(h) = 1 + 2a\frac{h}{b} + b\frac{h^2}{v^2} + \dots$$

Grinstein,Trott PRD 76 073002
Contino et al. JHEP 1005 089

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

adimensional

derivative expansion $\sim$ χPT

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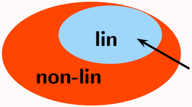
adimensional

derivative expansion $\sim$ χPT

$\longrightarrow$ a **very general** EFT



contains the linear as a particular limit

$\longrightarrow$ Indispensable for
- composite Higgs
- Higgs-dilaton
- strong interacting EWSB
- ...

Non-linear EFT for ALPs

$$\mathcal{L}_{\text{ALP, nonlin}} = \mathcal{L}_0 + \frac{1}{2}\partial_\mu a \partial^\mu a + i C_{2D} v^2 \, \text{Tr}(\mathbf{T}\mathbf{V}_\mu) \frac{\partial^\mu a}{f_a} \mathcal{F}_{2D}(h) + \Delta\mathcal{L}_a$$

$$\begin{aligned}\mathscr{L}_{\text{SM}} = &\,(\text{kinetic terms for } \psi, W, Z, \mathcal{G}) + \\ &+ \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \\ &- \frac{(v+h)^2}{4}\text{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu] + \\ &- \frac{v+h}{\sqrt{2}}\left[\bar{\psi}_L \mathbf{U} Y \psi_R + \text{h.c.}\right]\end{aligned}$$

GB kinetic terms
gauge bosons' masses

Yukawas

$$\mathbf{V}_\mu = D_\mu \mathbf{U}\mathbf{U}^\dagger \quad \xrightarrow{\text{unit.gauge}} \quad igW^I_\mu \sigma^I - g' B_\mu \sigma^3$$

$$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger \qquad\qquad \sigma^3$$

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$$\begin{aligned}\mathscr{L}_0 \quad &= (\text{kinetic terms for } \psi, W, Z, \mathcal{G}) + \\ &+ \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \\ &- \frac{\mathcal{F}_C(h)}{4}\,\text{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu] + \\ &- \frac{\mathcal{F}_Y(h)}{\sqrt{2}}\left[\bar{\psi}_L \mathbf{U} Y \psi_R + \text{h.c.}\right]\end{aligned}$$

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$$\mathcal{L}_{\text{ALP, nonlin}} = \mathcal{L}_0 + \frac{1}{2}\partial_\mu a \partial^\mu a + iC_{2D} v^2 \,\text{Tr}(\mathbf{TV}_\mu)\frac{\partial^\mu a}{f_a}\mathcal{F}_{2D}(h) + \Delta\mathcal{L}_a$$

unitary gauge: $\frac{g}{c_\theta f_a} Z^\mu \partial_\mu a \left(1 + a_{2D}\frac{h}{v} + b_{2D}\frac{h^2}{v^2} + \dots\right)$

$\mathcal{Q}_{aH} \leftrightarrow$

redefined via:

$\mathbf{U} \to \mathbf{U} \exp\left(2C_{2D}\frac{ia}{f_a}\right)\sigma^3$

replaced by

independent

aZh^n couplings survive
they are leading effects!

$\updownarrow$

$d = 7$ in the linear EFT

$$\mathcal{Q}^\psi_{aH} \leftrightarrow \quad \mathcal{Q}^\psi_{2D} = i\sqrt{2}v\frac{a}{f_a}\left[\bar{Q}_L \mathcal{Y}_Q \mathbf{U}\sigma^3 Q_R + \bar{L}_L \mathcal{Y}_L \mathbf{U}\sigma^3 L_R\right] + \text{h.c.}$$

Testing the aZh coupling

peculiar in the **non-linear** EFT → possible **discriminating** signatures

1 $\Gamma(\mathbf{h} \to \mathbf{Za}) < \Gamma(\mathbf{h} \to \mathbf{BSM}) < 2.1$ MeV (95% CL) ATLAS+CMS 1606.02266

$$\frac{f_a}{C_{2D}\, a_{2D}} \gtrsim 2.78 \text{ TeV}$$

setting to zero the other C_i
(C_{2D} gives the dominant contr.)

projection HL-LHC: **6** TeV

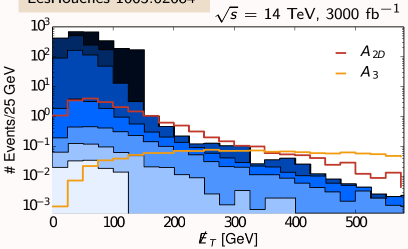
Testing the aZh coupling

peculiar in the **non-linear** EFT → possible **discriminating** signatures

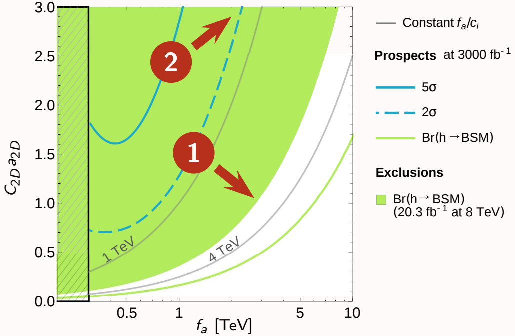
1. $\Gamma(h \to Za) < \Gamma(h \to BSM) < 2.1$ MeV (95% CL) ATLAS+CMS 1606.02266

2. **mono-Higgs** @ HL-LHC

LesHouches 1605.02684



prospects: $f_a/c_{2D} \gtrsim 780$ GeV



The constraint from $h \to$ BSM is already better than mono-H prospects

Non-linear EFT for ALPs

$$\mathcal{L}_{\text{ALP, nonlin}} = \mathcal{L}_0 + \frac{1}{2}\partial_\mu a \partial^\mu a + iC_{2D} v^2 \,\text{Tr}(\mathbf{T}\mathbf{V}_\mu)\frac{\partial^\mu a}{f_a}\mathcal{F}_{2D}(h) + \Delta\mathcal{L}_a$$

A complete basis for the CP even bosonic sector:

$$\mathcal{A}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathcal{A}_{\tilde{W}} = -W^I_{\mu\nu}\tilde{W}^{I\mu\nu}\frac{a}{f_a} \qquad \mathcal{A}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

same as in linear EFT

$$\mathcal{A}_1 = \tilde{B}_{\mu\nu}\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_1(h) \qquad \mathcal{A}_2 = \text{Tr}[\tilde{W}_{\mu\nu}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_2(h)$$

$$\mathcal{A}_3 = B_{\mu\nu}\partial^\mu\frac{a}{f_a}\partial^\nu\mathcal{F}_3(h) \qquad \mathcal{A}_4 = \text{Tr}[\mathbf{V}_\mu\mathbf{V}_\nu]\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_4(h)$$

$$\mathcal{A}_5 = \text{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\,\text{Tr}[\mathbf{T}\mathbf{V}^\nu]\partial_\nu\frac{a}{f_a}\mathcal{F}_5(h) \qquad \mathcal{A}_6 = \text{Tr}[\mathbf{T}[W_{\mu\nu},\mathbf{V}^\mu]]\partial^\nu\frac{a}{f_a}\mathcal{F}_6(h)$$

$$\mathcal{A}_7 = \text{Tr}[\mathbf{T}\tilde{W}_{\mu\nu}]\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_7(h) \qquad \mathcal{A}_8 = \text{Tr}[[\mathbf{V}_\nu,\mathbf{T}]D_\mu\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_8(h)$$

$$\mathcal{A}_9 = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\,\text{Tr}[\mathbf{T}\mathbf{V}_\nu]\partial^\nu\frac{a}{f_a}\mathcal{F}_9(h) \qquad \mathcal{A}_{10} = \text{Tr}[\mathbf{T}W_{\mu\nu}]\partial^\mu\frac{a}{f_a}\partial^\nu\mathcal{F}_{10}(h)$$

$$\mathcal{A}_{11} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\Box\frac{a}{f_a}\partial^\mu\mathcal{F}_{11}(h) \qquad \mathcal{A}_{12} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\partial^\nu\frac{a}{f_a}\partial_\nu\mathcal{F}_{12}(h)$$

$$\mathcal{A}_{13} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\frac{a}{f_a}\,\Box\,\mathcal{F}_{13}(h) \qquad \mathcal{A}_{14} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu\frac{a}{f_a}\partial^\mu\partial^\nu\mathcal{F}_{14}(h)$$

$$\mathcal{A}_{15} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\frac{a}{f_a}\partial_\nu\mathcal{F}_{15}(h)\partial^\nu\mathcal{F}'_{15}(h) \qquad \mathcal{A}_{16} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu\frac{a}{f_a}\partial^\mu\mathcal{F}_{16}(h)\partial^\nu\mathcal{F}'_{16}(h)$$

$$\mathcal{A}_{17} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\frac{\Box a}{f_a}\mathcal{F}_{17}(h)$$

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A complete basis for the CP even bosonic sector:

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same as in linear EFT

$$\mathcal{A}_1 = \tilde{B}_{\mu\nu}\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_1(h) \qquad \mathcal{A}_2 = \text{Tr}[\tilde{W}_{\mu\nu}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_2(h)$$

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$$\mathcal{A}_5 = \text{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\,\text{Tr}[\mathbf{T}\mathbf{V}^\nu]\partial_\nu\frac{a}{f_a}\mathcal{F}_5(h) \qquad \mathcal{A}_6 = \text{Tr}[\mathbf{T}[W_{\mu\nu},\mathbf{V}^\mu]]\partial^\nu\frac{a}{f_a}\mathcal{F}_6(h)$$

$$\mathcal{A}_7 = \text{Tr}[\mathbf{T}\tilde{W}_{\mu\nu}]\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_7(h) \qquad \mathcal{A}_8 = \text{Tr}[[\mathbf{V}_\nu,\mathbf{T}]D_\mu\mathbf{V}^\mu]\partial^\nu\frac{a}{f_a}\mathcal{F}_8(h)$$

$$\mathcal{A}_9 = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\text{Tr}[\mathbf{T}\mathbf{V}^\mu]\,\text{Tr}[\mathbf{T}\mathbf{V}_\nu]\partial^\nu\frac{a}{f_a}\mathcal{F}_9(h) \qquad \mathcal{A}_{10} = \text{Tr}[\mathbf{T}W_{\mu\nu}]\partial^\mu\frac{a}{f_a}\partial^\nu\mathcal{F}_{10}(h)$$

17 more invariants

$$\mathcal{A}_{11} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\,\Box\frac{a}{f_a}\partial^\mu\mathcal{F}_{11}(h) \qquad \mathcal{A}_{12} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\partial^\nu\frac{a}{f_a}\partial_\nu\mathcal{F}_{12}(h)$$

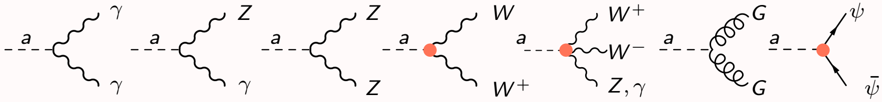
$$\mathcal{A}_{13} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\frac{a}{f_a}\Box\mathcal{F}_{13}(h) \qquad \mathcal{A}_{14} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu\frac{a}{f_a}\partial^\mu\partial^\nu\mathcal{F}_{14}(h)$$

$$\mathcal{A}_{15} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\frac{a}{f_a}\partial_\nu\mathcal{F}_{15}(h)\partial^\nu\mathcal{F}'_{15}(h) \qquad \mathcal{A}_{16} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu\frac{a}{f_a}\partial^\mu\mathcal{F}_{16}(h)\partial^\nu\mathcal{F}'_{16}(h)$$

$$\mathcal{A}_{17} = \text{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\frac{\Box a}{f_a}\mathcal{F}_{17}(h)$$

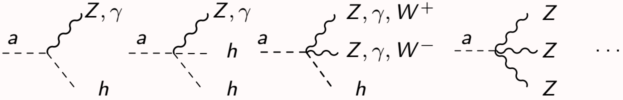
EFT for ALPs – extending the picture

linear EFT

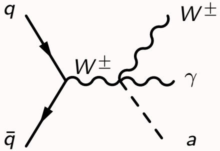


+ more Lorentz structures

non-linear EFT



Non-linear effects in aWγ production



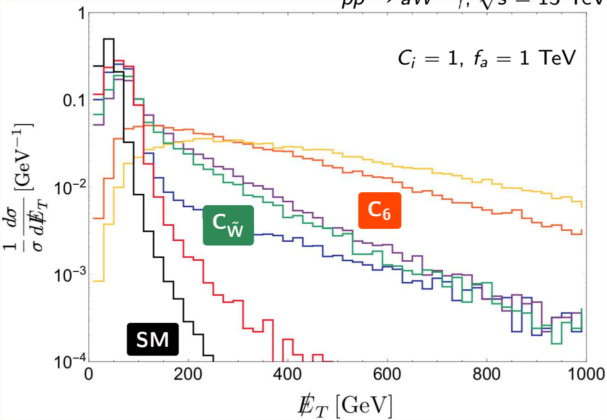
Many non-linear operators contributing!

Within LHC reach:

$$\mathcal{A}_{\tilde{W}} \sim W^I_{\mu\nu}\tilde{W}^{I\mu\nu} a/f_a$$

$$\mathcal{A}_6 \sim \text{Tr}(\mathbf{T}[W_{\mu\nu}, \mathbf{V}^\mu])\partial^\nu a/f_a$$

$pp \to aW^+\gamma$, $\sqrt{s} = 13$ TeV



projection HL-LHC
(one at a time)

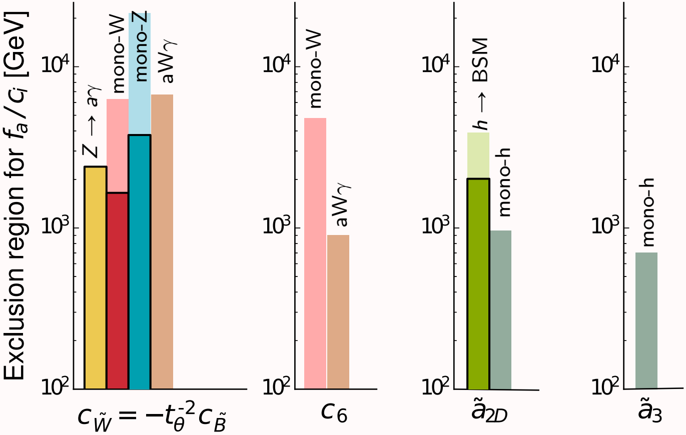
$$\frac{f_a}{C_{\tilde{W}}} \gtrsim 6.8 \text{ TeV}$$

$$\frac{f_a}{C_6} \gtrsim 0.95 \text{ TeV}$$

Summary

we have looked for **ALPs** with an EFT approach

- looked at new collider constraints on the ALP EFT



Summary

we have looked for **ALPs** with an EFT approach

- looked at new collider constraints on the ALP EFT
- first time: non-linear EFT : 17 more operators
  - more couplings (**Higgs**! → best tested in (h → BSM))
  - more Lorentz structures → some within LHC reach

More ALPs @ Colliders

- optimize analyses (e.g. with multivariate analyses)
- include more operators at the same time
  → possible to **distinguish non-linear** effects?
- combine different channels to disentangle different (non-linear!) operators
  e.g.: aW(γ) ↔ VBF $ajj(\gamma)$ mono-W ↔ mono-Z
- beyond this EFT: test heavier masses (decaying ALPs)
- . . .

Backup slides

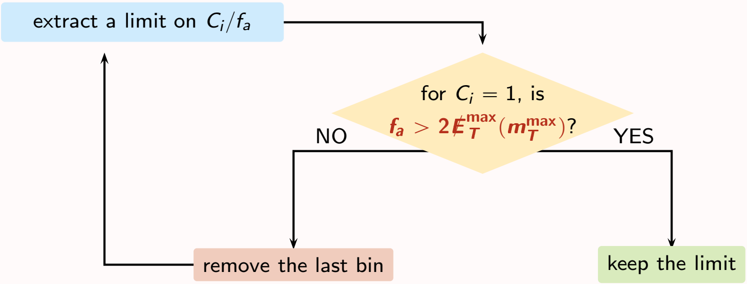
EFT validity

The EFT is a valid description for $\sqrt{\hat{s}} \lesssim f_a$
→ the bound is consistent if this is verified for *all* the events used

! $\sqrt{\hat{s}}$ is not accessible experimentally

mono-Z → $\not{E}_T$
mono-W → $m_T \equiv \left(2p_T^\ell \not{E}_T (1 - \cos\phi)\right)^{1/2}$

Basic algorithm:



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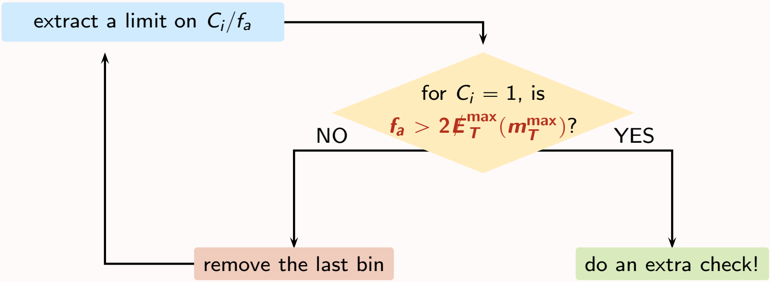
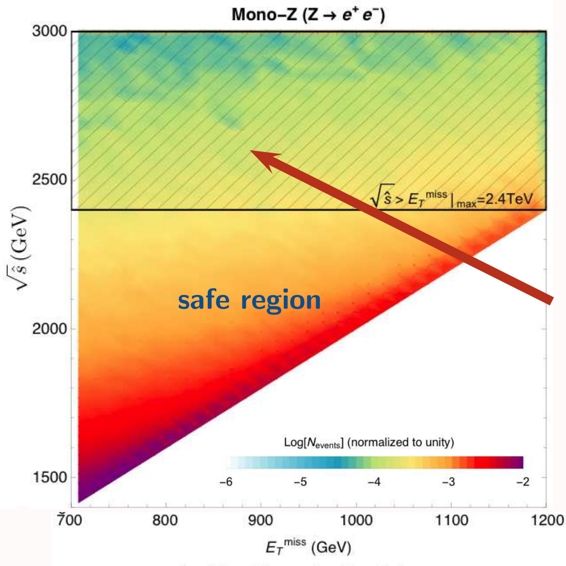


EFT validity

Extra check: correlations of $\not{E}_T$ (m_T) with $\sqrt{\hat{s}}$

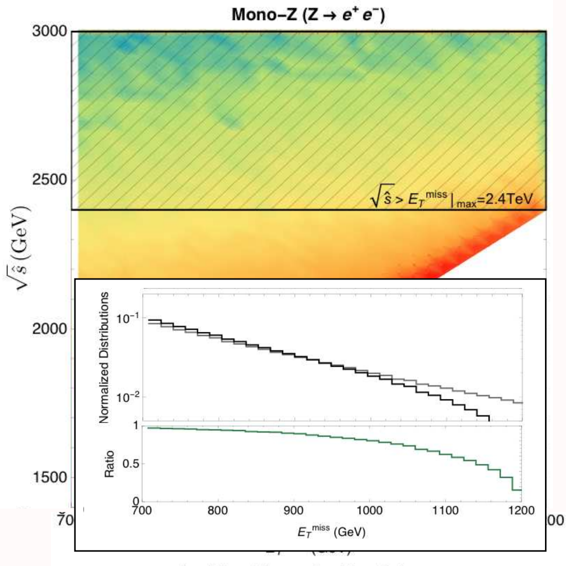


distribution of signal events (MadGraph simulation) in the $(\not{E}_T, \sqrt{\hat{s}})$ plane

these events have been included but the EFT is not valid here!

EFT validity

Extra check: correlations of $\not{E}_T$ (m_T) with $\sqrt{\hat{s}}$



distribution of signal events (MadGraph simulation) in the $(\not{E}_T, \sqrt{\hat{s}})$ plane

removing them reshapes the signal distribution

↓

few % correction on our C_i/f_a limits

(larger for weaker limits)

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

mono W/Z: statistical analysis

binned likelihood analysis

$$L^\ell(\mu_i) = \prod_k e^{-(\mu_i\, s_k^i + b_k)} \frac{(\mu_i\, s_k^i + b_k)^{n_k}}{n_k!}$$

$\mu_i \equiv (c_i/f_a)^2$
$\ell = e,\, \mu$ final state lepton
b_k background pred.
s_k^i signal pred. $C_i = 1,\ f_a = 1$ TeV

significance: $Q^\ell_{\mu_i} \equiv -2 \log\left[\frac{L^\ell(\mu_i)}{L^\ell(\hat{\mu}_i)}\right]$

$\hat{\mu}_i =$ the value of μ_i that maximizes $L^\ell(\mu_i)$

with systematics on the background prediction

$$L^\ell_S(\mu_i) = \prod_k \int_0^\infty dr\, \frac{e^{\frac{-(r-1)^2}{2\sigma_k^2}}}{\sqrt{2\pi}\sigma_k}\, e^{-(\mu_i\, s_k^i + r\, b_k)} \frac{(\mu_i\, s_k^i + r\, b_k)^{n_k}}{n_k!}\,,$$

σ_k = background systematic uncertainty

$$Q^\ell_{S\,\mu_i} = -2\,\mathrm{Log}\left[\frac{L^\ell_S(\mu_i)}{L^\ell_S(\hat{\mu}_i)}\right]$$

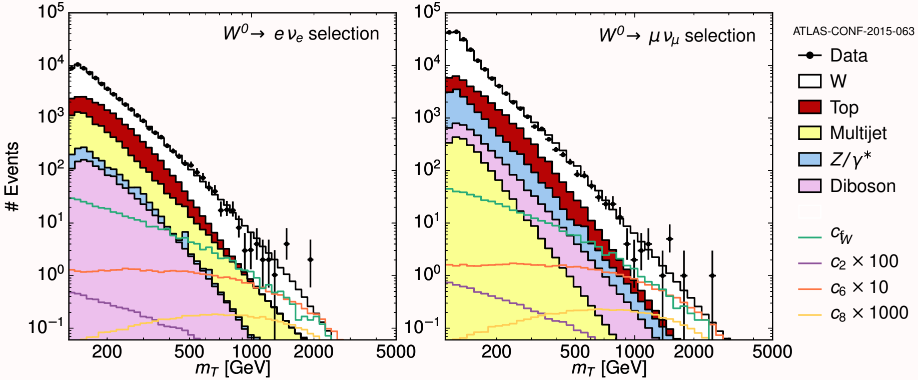
mono-W analysis

[b] Selection cuts: ATLAS-CONF-2015-063

	e	μ
$p_T >$ (GeV)	65	55
$\not{E}_T >$ (GeV)	65	55
$m_T >$	130	110

Constraints on $C_{\tilde{W}}$

		e	μ
$\left(f_a/c_{\tilde{W}}\right)_{\min}$ [TeV]		1.28	1.65
$\left(f_a/c_{\tilde{W}}\right)_{\min}$ [TeV]	[No Syst.]	1.72	2.46



mono-Z analysis

Selection cuts CMS-PAS-EXO-16-010

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

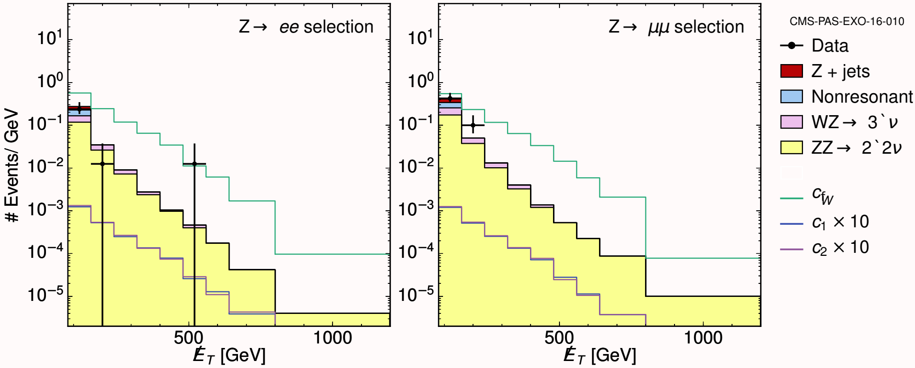
$$m_{\ell\ell} \in [80,\ 100] \text{ GeV}, \not{E}_T > 80 \text{ GeV}$$

$$\left|\not{E}_T - p_T^{\ell\ell}\right| / p_T^{\ell\ell} < 0.2, \Delta\phi_{\ell\ell,\vec{\not{E}}_T} > 2.7 \text{ (rad)}$$

+ 3rd-lepton and extra high-p_T jets vetoes

Constraints on $C_{\tilde{W}}$

		e	μ
$(f_a/c_{\tilde{W}})_{\min}$ [TeV]		3.77	2.54
$(f_a/c_{\tilde{W}})_{\min}$ [TeV]	[No Syst.]	3.79	2.54



mono W/Z projections

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

	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

aWγ analysis - technical details

Backgrounds

ATLAS 1302.1283
CMS 1308.6832]

dominant: $pp \to W^\pm\gamma$ (with $W^\pm \to \ell^\pm\nu$)

subdominant: (*i*) $W^\pm$+jets → combined: increase $W^\pm\gamma$ bg by 15-25%
(*ii*) $Z\,\ell^+\ell^-, Z \to \nu\bar\nu$
(*iii*) γ+jets
(*iv*) $t\bar t$ (semileptonic)

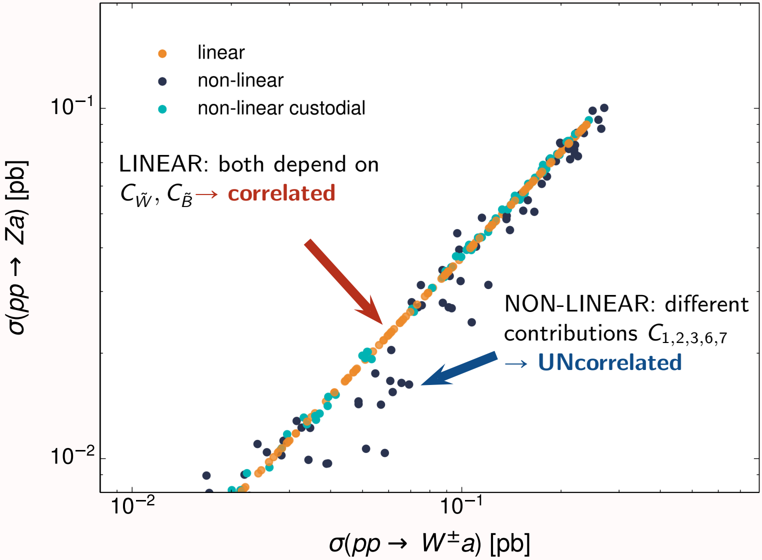
→ we scale up by 20% the measurement of $W^\pm\gamma$ SM

Selection cuts $p_T^\gamma > 20\,\mathrm{GeV}$, $p_T^\ell > 20\,\mathrm{GeV}$, $|\eta^\gamma| < 2.5$, $|\eta^\ell| < 2.5$, $\not{E}_T > 200$ GeV.

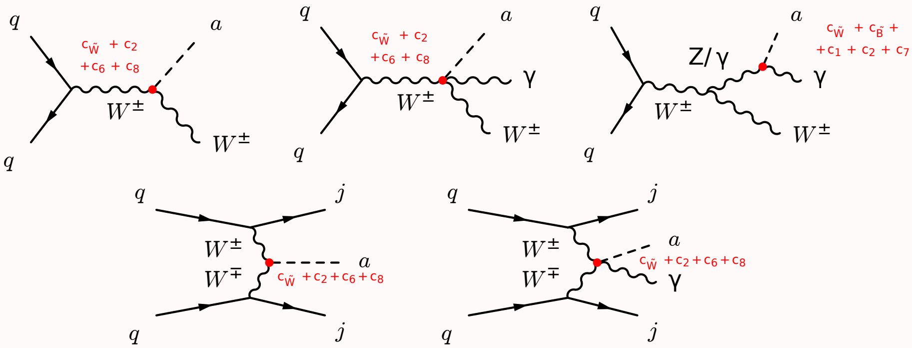
significance $\sigma_i = \sqrt{2\left[(\mu_i s_i + b)\ln\left(1+\frac{\mu_i s_i}{b}\right) - \mu_i s_i\right]}$

with $s_i = \mathcal{L} \times \int_{\not{E}_T^{\text{min}}}^{f_a/2} \frac{d\sigma_i}{\not{E}_T} d\not{E}_T$, $\quad b = \mathcal{L} \times \int_{\not{E}_T^{\text{min}}}^{f_a/2} \frac{d\sigma_{\text{SM}}}{d\not{E}_T} d\not{E}_T$, $\quad \mathcal{L}$ = integrated lumi

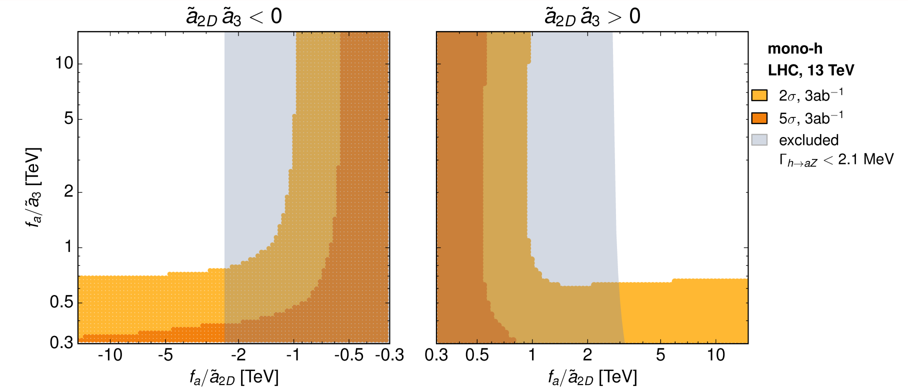
mono-W vs mono-Z



Combination of $aW(\gamma)$ and $ajj(\gamma)$ in VBF



mono-Higgs with both c_{2D} and c_3



Complete basis: linear

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

$$\mathcal{Q}_{\tilde{W}} = -W^I_{\mu\nu}\tilde{W}^{I\mu\nu}\frac{a}{f_a}$$

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

$$\mathcal{Q}_{\psi} = \bar{\psi}\gamma_\mu\psi\frac{\partial^\mu a}{f_a}, \qquad \psi = \{\ell_L, q_L, u_R, d_R, e_R\}$$

where $\mathcal{Q}_\psi$ has generic flavor contractions

$\rightarrow \mathcal{Q}_{aH}$ becomes redundant

Complete basis: non-linear

Additional fermionic operators:

$$\mathbf{B}_1^q = \bar{Q}_L \mathbf{U} Q_R \, \partial_\mu \frac{a}{f_a} \partial^\mu \mathcal{F}(h)$$

$$\mathbf{B}_2^q = \bar{Q}_L \mathbf{T} \mathbf{U} Q_R \, \partial_\mu \frac{a}{f_a} \partial^\mu \mathcal{F}(h)$$

$$\mathbf{B}_3^q = \bar{Q}_L \mathbf{V}_\mu \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_4^q = \bar{Q}_L \{\mathbf{V}_\mu, \mathbf{T}\} \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_5^q = \bar{Q}_L [\mathbf{V}_\mu, \mathbf{T}] \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_6^q = \bar{Q}_L \mathbf{T} \mathbf{V}_\mu \mathbf{T} \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_7^q = \bar{Q}_L \sigma^{\mu\nu} \mathbf{V}_\mu \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_8^q = \bar{Q}_L \sigma^{\mu\nu} \{\mathbf{V}_\mu, \mathbf{T}\} \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_9^q = \bar{Q}_L \sigma^{\mu\nu} [\mathbf{V}_\mu, \mathbf{T}] \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_{10}^q = \bar{Q}_L \sigma^{\mu\nu} \mathbf{T} \mathbf{V}_\mu \mathbf{T} \mathbf{U} Q_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_1^\ell = \bar{L}_L \mathbf{U} L_R \, \partial_\mu \frac{a}{f_a} \partial^\mu \mathcal{F}(h)$$

$$\mathbf{B}_2^\ell = \bar{L}_L \{\mathbf{V}_\mu, \mathbf{T}\} \mathbf{U} L_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_3^\ell = \bar{L}_L [\mathbf{V}_\mu, \mathbf{T}] \mathbf{U} L_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_4^\ell = \bar{L}_L \sigma^{\mu\nu} \{\mathbf{V}_\mu, \mathbf{T}\} \mathbf{U} L_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

$$\mathbf{B}_5^\ell = \bar{L}_L \sigma^{\mu\nu} [\mathbf{V}_\mu, \mathbf{T}] \mathbf{U} L_R \, \partial^\mu \frac{a}{f_a} \mathcal{F}(h)$$

with these terms, the bosonic $\mathcal{A}_8, \mathcal{A}_{11}, \mathcal{A}_{13}, \mathcal{A}_{17}$ become redundant