

Les Rencontres de Physique de la Vallée d'Aoste La Thuile, Aosta Valley, 15 March 2019

Recent Progress on ALPs

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based on work with M. Bauer, A. Thamm & M. Heiles: 1704.08207 (PRL), 1708.00443 (JHEP) & 1808.10323 (EPJC)VERSI

Motivation

 $Re \phi$

 $\text{Im}\,\phi$

- ❖ **Axion-like particles** (ALPs) appear in many BSM scenarios and are well motivated: strong CP problem, mediator to hidden sector, pNGB of spontaneously broken global symmetry, explanation of $(g-2)_{\mu}$, ...
- ❖ Assume the existence of a new pseudoscalar resonance *a*, which is a SM singlet and whose mass is protected by a (approximate) shift symmetry *a*→*a+const.*
- How can one probe such an ALP at colliders?

[previous studies: Kim, Lee 1989; Djouadi, Zerwas, Zunft 1991; Rupak, Simmons 1995; Kleban, Ramadan 2005; Mimasu, Sanz 2014; Jäckel, Spannowsky 2015; Knapen, Lin, Lou, Melia 2016; Brivio et al. 2017; …]

Effective Lagrangian 2 E↵ective Lagrangian for ALPs WE a new spin-0 resonance of a new spin-0 resonance a new spin-0 resonance and spingauge group. Its mass *m^a* is assumed to be smaller than the electroweak scale. A natural way

to get such a light particle is by imposing a shift symmetry, *a* ! *a* + *c*, where *c* is a constant.

* The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale): $m = 1$ ective Lagrangian including operators of dimension up to 5 (written in the 5 μ the effective Lagrangian (with $\Lambda=32$ $\Lambda = 32\pi^2 f_a |C_{GG}|$

$$
\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2} \left(\partial_{\mu} a \right) \left(\partial^{\mu} a \right) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^{\mu} a}{\Lambda} \sum_{F} \bar{\psi}_F \mathbf{C}_F \gamma_{\mu} \psi_F
$$
\n
$$
+ g_s^2 C_{GG} \frac{a}{\Lambda} G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + g^2 C_{WW} \frac{a}{\Lambda} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + g'^2 C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu}
$$
\n[Georgi, Kaplan, Randall 1986]

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$$
\n
$$
e^{2} C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^{2}}{s_{w} c_{w}} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^{2}}{s_{w}^{2} c_{w}^{2}} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu}
$$
\n
$$
(C_{\gamma\gamma} = C_{WW} + C_{BB} \text{ etc.})
$$

Effective Lagrangian **F***Fffe s*2 *wc*² *w CZZ* ⇤ *^Zµ*⌫ *^Z*˜*µ*⌫ *,* (4) 2 E↵ective Lagrangian for ALPs WE a new spin-0 resonance of a new spin-0 resonance a new spin-0 resonance and spingauge group. Its mass *m^a* is assumed to be smaller than the electroweak scale. A natural way

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$$
\n
$$
+ g_{s}^{2} C_{GG} \frac{a}{\Lambda} G_{\mu\nu}^{A} \tilde{G}^{\mu\nu,A} / \int g^{2} C_{WW} \frac{a}{\Lambda} W_{\mu\nu}^{A} \tilde{W}^{\mu\nu,A} + g^{\prime 2} C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu}
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$$
\n
$$
\sum_{f} \frac{c_{ff}}{2} \frac{\partial^{\mu} a}{\Lambda} \bar{f} \gamma_{\mu} \gamma_{5} f + \text{flavor off-diagonal terms}
$$
\n
$$
(C_{\gamma\gamma} = C_{WW} + C_{BB} \text{ etc.})
$$

plings of the pseudoscalar *a* to , *Z* and *ZZ*. The relevant terms read

Effective Lagrangian $LillullU$ using it can be reduced to the feature operators in $Lill$ equations [20], contributing an extra term *cf f* ⁼ 2*T^f* ³ to the coecients *cf f* defined in 2 E↵ective Lagrangian for ALPs WE a new spin-0 resonance of a new spin-0 resonance a new spin-0 resonance and spingauge group. Its mass *m^a* is assumed to be smaller than the electroweak scale. A natural way

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(@*^µa*)

* The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale): In our discussion we will be again will be again will be again the values of the W leads and al- $\mathcal{O}(n)$ s_{th} of footing I aggregation (with $\Lambda = 2f(\Lambda)$ to Λ I could) concentre Lagrangian (with $\Lambda = 92\pi / Ja$ $|CGG|$ a is start). $m = 1$ ective Lagrangian including operators of dimension up to 5 (written in the 5 μ the effective Lagrangian (with $\Lambda=32$ $\Lambda = 32\pi^2 f_a |C_{GG}|$

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❖ At D=6 order and higher, additional interactions arise: λ *v*. At die λ \sim λ At $D=6$ order and higher, a where we higher additional intersections arises At D=0 order and higher, additional interactions arise:

$$
\mathcal{L}_{\text{eff}}^{D\geq 6}=\frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi+\frac{C_{Zh}^{(7)}}{\Lambda^3}\,(\partial^\mu a)\,\big(\phi^\dagger\,iD_\mu\,\phi+\text{h.c.}\big)\,\phi^\dagger\phi+\dots
$$

- ❖ Our goal is to probe scales **Λ~1-100 TeV** at the LHC 2 s^2 invariant at one-loop order (see e.g. s^2 Our goal is to probe scales **A~1-I00 IeV** at the LHC
- ❖ Include one-loop corrections in production and decay rates Indude and *Jean corrections* in production and decay rates *a a* equal to the act of the Contribution of the coupling of the coupling to α

 μ suppression-5 operators with a new-physics scale \mathbf{I} , which is the characteristic scale \mathbf{I} M. Neubert: Recent progress on ALPs (La Thuile 2019) 2'

Example: ALP decay into photons of its special importance, we have calculated the corresponding decay rate from the e↵ective 3.1 ALP decay into photons In many scenarios, the dominant decay is the dominant decay is the dominant decay is the dominant decay mode o \blacksquare is special inportance, we have corresponding the corresponding the corresponding to the e \blacksquare Lauring to the cover the phonediagrams are shown in Figure 1. We define an e↵ective coecient *C*^e↵

Lagrangian (1) including the complete set of one-loop corrections. The relevant Feynman

such that the control of

❖ Including the complete set of one-loop corrections, we obtain from the effective Lagrangian: \ddot{a} . Its special importance, we have calculated the corresponding decay rate from the e \ddot{a} *a* \overline{I} ve Lagrai $logian$ obtain from the effective Lagrangian:
 $E(z) = \frac{4\pi\alpha^2 m_a^3}{\sqrt{e^{\pi}L^2}}$ Including the complete set of one-loop corrections, we *complete set* **S6** C $\sum_{i=1}^{n}$ obtain from the offective I equation: obtain from the effective Lagrangian.

$$
\Gamma(a\rightarrow\gamma\gamma)\equiv\frac{4\pi\alpha^2m_a^3}{\Lambda^2}\,|C_{\gamma\gamma}^{\text{eff}}|^2
$$

where $(\tau_i \equiv 4m_i^2/m_a^2)$: $\binom{2}{a}$: the *a* ! decay rate scales with the third power of the ALP mass. For a very light ALP $\sum_{i=1}^{\infty}$ involving colored particles, can be evaluated in perturbation that $\sum_{i=1}^{\infty}$

V = *G, W, B*) are loop suppressed.

3.1 ALP decay into photons

$$
C_{\gamma\gamma}^{\text{eff}}(m_a \gg \Lambda_{\text{QCD}}) = C_{\gamma\gamma} + \sum_f \frac{N_c^f Q_f^2}{16\pi^2} c_{ff} B_1(\tau_f) + \frac{2\alpha}{\pi} \frac{C_{WW}}{s_w^2} B_2(\tau_W)
$$

3.1 ALP decay into photons and the control of the
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3.

M. Neubert: Recent progress on ALPs (La Thuile 2019) 3

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Z^e *diagrams obtain from the effective Lagrangian:* **eian:**
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3.

$$
C_{\gamma\gamma}^{\text{eff}}(m_a \lesssim 1 \,\text{GeV}) \approx C_{\gamma\gamma} - (1.92 \pm 0.04) C_{GG} - \frac{m_a^2}{m_{\pi}^2 - m_a^2} \left[C_{GG} \frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{32\pi^2} \right]
$$

$$
+ \sum_{q=c,b,t} \frac{N_c Q_q^2}{16\pi^2} c_{qq} B_1(\tau_q) + \sum_{\ell=e,\mu,\tau} \frac{c_{\ell\ell}}{16\pi^2} B_1(\tau_{\ell}) + \frac{2\alpha}{\pi} \frac{C_{WW}}{s_w^2} B_2(\tau_W)
$$

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Pattern of decay rates

* Assuming that the relevant Wilson coefficients are equal to 1/TeV, we find the following pattern of decay rates:

Constraints on C_{γγ} and c_{ee}

[Armengaud et al. 2013; Jäckel, Spannowsky 2015; many others …] F ininchgaaa et an. 2010, jacker, oparition che Z 010, many othero $...$

 $\frac{1}{10}$

- ❖ Anomaly can be reproduced for $O(1)$ Wilson coefficients $C_{\gamma\gamma}$ and $C_{\mu\mu}$ B_{abbar} excess α **EXHOILE TEV, which one can be one** $\lim_{\mu \to 0} \frac{1}{\mu}$ of $\lim_{\mu \to 0} \frac{1}{\mu}$ of $\lim_{\mu \to 0} \frac{1}{\mu}$ of $\lim_{\mu \to 0} \frac{1}{\mu}$ $\text{coefficients } \cup_{\gamma\gamma} \text{ and } c_{\mu\mu}$ shown in Figure 3. The most contributions of the most contribu **highly for** $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (288 \pm 63 \pm 49) \cdot 10^{-11}$ **[28]** $\frac{20}{\pi}$ and $\frac{10}{\pi}$ *a*^{eff} (A FE $\begin{bmatrix} 10 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$
- **EXECUTE:** BaBar search for [BaBar: 1606.03501] significantly constrains the allowed parameter space (grey) An important constraint on the ALP–photon and ALP–muon couplings, *C* and *cµµ*, $e^+e^- \to \mu^+\mu^- + Z' \to \mu^+\mu^- + \mu^+\mu^ \frac{1}{2}$ hints for new physics. The di↵erence *a*exp $\frac{1}{2}$ **from** $\frac{1}{2}$ $\frac{2}{2}$ $\frac{1}{2}$ $\frac{2}{2}$ $\frac{1}{2}$ $\frac{$ \triangleq BaBar search for [BaBar: 1606.03501] $\frac{1}{2}$ $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ $\begin{bmatrix} \mu & \mu \\ \mu & \mu \end{bmatrix}$ μ μ μ μ μ allowed parameter space (grey)²⁵ $e^+e^- \rightarrow \mu^+\mu^- + Z' \rightarrow \mu^+\mu^- + \mu^+\mu^$ complete one-loop analysis, we find that our model gives \leq \overline{par} amete *r space* (gr
	- ◆ Tighter constraints expected from
Belle **II** Belle II ∗ Ilgner c
Belle II ↵ Bel *n*_{*II*} *C*

 $\sum_{R_{na}=3~\text{GeV}}$ (gaselving the set of the se

M. Neubert: Recent progress on ALPs (La Thuile 2019) 6 assume *Ka^µ* (⇤) = 0 at ⇤ = 1 TeV and neglect the tiny contribution proportional to *CZ*. For denotes the coecient of the operator in the *D* =6e↵ective Lagrangian of the

Higgs Decays as an ALP Factory

[see also: Dobrescu, Landsberg, Matchev 2000; Chang, Fox, Weiner 2006; Draper, McKeen 2012; Curtin et al. 2013]

On-shell Higgs decays into ALPs

- ❖ Effective Lagrangian allows for *h*→*Za* and *h*→*aa* decays at rates likely to be accessible in the high-luminosity run of LHC (already with 300 fb-1)
- Branching ratios can reach 10%

***** Higgs physics provides powerful observatory for ALPs in the mass range between 1 MeV and 60 GeV, which is otherwise not easily accessible to experimental searches **a**
b
b bound Br(*h* ! BSM) *<* 0*.*34 (orange) derived from the global analysis of Higgs decays [98]. The ween 1 MeV and 60 GeV, which is ween I we v and ou Ge v, Note that the second Higgs-portal interaction in \mathbf{A}_{in} approximation in this approximation, \mathbf{A}_{in}

Example: Exotic decay h→aa \blacksquare provides for the through modes in where the e Γ as by loop-mediated dimension-fraction-fraction-fraction-fraction-fraction-fraction-fraction-fraction-fractionhave calculated the *h* ! *aa* decay rate including the tree-level Higgs-portal interactions as well as all one-loop corrections arising from two insertions are corrections of operators from the dimension-lo

calculated the *h* ! *aa* decay rate including the tree-level Higgs-portal interaction as well as

³↵

 5.5 ± 0.01 e 1.4 ± 0.01 and the relevant diagrams are shown in Figure 14. Since both the relevant diagrams are shown in 1.4 ± 0.01

ln *^µ*²

By means of the Higgs portal interaction interaction-6 election-6 election-6 election-6 election-6 election-6 e
The dimension-6 election-6 election-6 election-6 election-6 election-6 election-6 election-6 election-6 electi

* Higgs portal interaction and loop-mediated processes allow for ALP pair production in Higgs decay: *v* Thggs portal interaction and loop-inequated processes *W* ץ יסנ
מז אוו *v* for AL ln *^µ*² $\overline{\text{rc}}$ ALP pair production in His rtal interaction and loop-mediated processes ✓

$$
\Gamma(h \to aa) = \frac{|C_{ah}^{\text{eff}}|^2}{32\pi} \frac{v^2 m_h^3}{\Lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right) \sqrt{1 - \frac{4m_a^2}{m_h^2}}
$$

with:

ah ⁼ *^Cah*(*µ*) + *^N^c ^y*²

tt

ln *^µ*²

$$
C_{ah}^{\text{eff}} = C_{ah}(\mu) + \frac{N_c y_t^2}{4\pi^2} c_{tt}^2 \left[\ln \frac{\mu^2}{m_t^2} - g_1(\tau_{t/h}) \right] + \dots
$$

$$
\approx C_{ah}(\Lambda) + 0.173 c_{tt}^2 - 0.0025 (C_{WW}^2 + C_{ZZ}^2)
$$

◆ A 10% branching ratio is obtained for 4⇡*s*² *wc*² ✓*g*² \overline{C} $\frac{1}{2}$ *ing ratio m*² is obtained $\overline{1}$ \triangle A 10% branching ratio is obtained for $|C_{ah}^{\text{eff}}| \approx 0.62 \, (\Lambda/\text{TeV})^2$ $\frac{1}{2}$ coupling $\frac{1}{2}$ and $\frac{1}{2}$ coupling is $\frac{1}{2}$ coupling is $\frac{1}{2}$ coupling is induced it $\frac{1}{2}$ coupling is induced it $\frac{1}{2}$ coupling is induced it $\frac{1}{2}$ coupling in $\frac{1}{2}$ coupling is i *x x*² *x x*

 $\frac{1}{2}$. Productive need to progress on the space of a mand $\frac{201}{2}$ M. Neubert: Recent progress on ALPs (La Thuile 2019) 8 the four-lepton or four-photon channels. For light ALPs, the large boost factors can lead to Neubert: Recent progress on ALPs (La Thuile 2019) **8**

Example: Exotic decay h→aa

- ❖ Depending on ALP decay modes, several interesting final-state signatures can arise:
	- ❖ *h*→*aa*→*γγ+γγ*, where the two photons in each pair are either resolved (for m_a $>$ \sim 100 MeV) or appear as a single photon in the calorimeter (adds to *h*→*γγ* signal)

$$
h \rightarrow aa \rightarrow l^{+}l^{-} + l^{+}l^{-}
$$
 with $l = e, \mu, \tau$

- ❖ *h*→*aa*→*4j*, including heavy-quark jets, …
- ❖ Most of these decays can be reconstructed

Decay-length effect *^a*)*/*(2*mamh*) for *h* ! *Za* and *^a* = *mh/*(2*ma*) for *h* ! *a* Decay length effect *^f*dec = 1 *^eL*det*/L^a* (8) *a^a a* σ σ τ *a* a letter in the letter is the two started terminal rate that the *argencer excess* is a letter that $\frac{1}{2}$ $\frac{d}{dx}$ **.** $\frac{d}{dx}$ **.** $\frac{d}{dx}$. $\frac{d}{dx}$ *a^a* **d** Ω *^a* ¹ Br(*^a* ! *XX*)

In the rest frame of the rest frame of the Higgs boson, $\mathbb{E}[\mathcal{E}(\mathbf{z})]$ boson, $\mathbb{E}[\mathcal{E}(\mathbf{z})]$ boson, $\mathbb{E}[\mathcal{E}(\mathbf{z})]$ boson, $\mathbb{E}[\mathcal{E}(\mathbf{z})]$ boson, $\mathbb{E}[\mathcal{E}(\mathbf{z})]$ boson, $\mathbb{E}[\mathcal{E}(\mathbf{z})]$

 \triangleq Weakly coupled light ALPs can have a ECAL macroscopic decay length, hence only a fraction *f*dec decays inside detector macroscopic docay lopath hopes only macroscopic accay ici $\frac{d}{dx}$ $\frac{d}{dx}$ $\frac{d}{dx}$ (8) $\frac{d}{dx}$ (8) $\frac{d}{dx}$ (8) $\frac{d}{dx}$ $\frac{1}{\sqrt{2}}$ *M* **a** *a a a <i>a**n* *****n <i>a <i>n n <i>a l*** ***n <i>a n n l*** ***n l*** ***n l*** ***n l*** ***n l n l l***** *l*** ***l l*** ***l l l*** ***l macroscopic decay length, hence only* and the *fraction of the set of the set* $\begin{bmatrix} 1: 1: A \text{ I} \text{ D} \end{bmatrix}$ is $\begin{bmatrix} 1: 1 \end{bmatrix}$ *m*² *^a*)*/*(2*mamh*) for *h* ! *Za* and *^a* = *mh/*(2*ma*) for *h* !

is good enough!] the boost factor is *^a* = (*m*²

❖ We define effective branching ratios: Br(*^h* ! *Za* ! `⁺`*XX*) ^e↵ = Br(*h* ! *Za*) We define effective branching ratios:

*^h ^m*²

In the rest frame of the rest frame of the Higgs boson, [Explain why this is the Higgs boson, [Explain why thi
In this case of this case of the Higgs boson, [Explain why this is the Higgs boson, [Explain why this is the H

^Z +

 $Br(h \rightarrow aa \rightarrow 4X)$ $\overline{\mathbf{I}}$ \int_{eff} = Br($h \to aa$) Br($a \to XX$)² f_{dec}^2 $\mathbf{D}_p(h \to \alpha \alpha + AV)$ $\mathbf{D}_p(h \to \alpha \alpha) \mathbf{D}_p(\alpha + VV)^2$ t^2 $\mathbf{E}[\mathbf{u} \times \mathbf{u} \mathbf{u}] \geq \mathbf{E}[\mathbf{u}]$ \overline{D} (1) \overline{D} (\overline{Y} \overline{Y}) define the thus define the thus define the thus define the thus define the three theory. $\mathcal{C}|_{\text{eff}} = \text{Br}(n \rightarrow au) \text{Br}(a -$ Figure 7: Sketch of the decay *h* ! *Za* ! *Z* in a vertical cross section of the detector with the χ and $\text{Br}(a \times Y)^2$ \hat{t}^2 .

$$
Br(h \to Za \to \ell^+ \ell^- XX)|_{eff} = Br(h \to Za)
$$

$$
\times Br(a \to XX) f_{dec} Br(Z \to \ell^+ \ell^-)
$$

❖ Even for *La* >> *L*det there remains some sensitivity Even for $L_z \gg L_{\text{det}}$ there remains some sensitivity son coecients *CZh* or *Cah*, we can now present the reach Even for $L_a >> L$ $\overline{1}$ det *there remains some sensitivity* \overline{a} $\boldsymbol{\delta}$ some sensitivity become maintains and hence only a small fraction of \mathbf{S} t_{total} is good and bosons at the L_{total}

of high-luminosity LHC searches for *^h* ! *Za* ! `⁺` M. Neubert: Recent progress on ALPs (La Thuile 2019) 10 where Br(*^Z* ! `⁺`)=0*.*0673 for ` ⁼ *e, µ*. If the

parameter region in which the (*g* 2)*^µ* anomaly can be

number of signal events inside the probed contour re-

pling remains perturbative. (In principle, larger values of

small if Br(*a* ! *XX*) falls below a critical value.

Probing the ALP-photon coupling

❖ Higgs analyses at the LHC (Run-2, 300 fb-1) will be able to explore a large region of uncovered parameter space:

Figure 4: Existing constraints on the ALP–photon (left) and ALP–electron coupling (right) derived M. Neubert: Recent progress on ALPs (La Thuile 2019) 11

Probing the ALP-photon coupling

❖ Higgs analyses at the LHC (Run-2, 300 fb-1) will be able to explore a large region of uncovered parameter space:

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- \triangleq Region preferred by $(g-2)_{\mu}$ can be covered completely!
- ❖ The ALP-photon coupling can be probed even if the ALP decays predominantly to other particles!

 $|C_{ah}^{\text{eff}}| = 1$, $\text{Br}(a \to \gamma \gamma) > 0.006$ $|C_{ah}^{\text{eff}}| = 0.1, \text{ Br}(a \to \gamma \gamma) > 0.049$ $|C_{ah}^{\text{eff}}| = 0.01, \text{ Br}(a \to \gamma \gamma) > 0.49$ (for $\Lambda = 1 \text{ TeV}$)

Probing the ALP-lepton couplings

❖ Higgs analyses at the LHC (Run-2, 300 fb-1) will be able to explore a large region of uncovered parameter space:

Babar 103 $|C_{ah}^{\text{eff}}| = 0.01$, $Br(a \rightarrow e^+e^-) > 0.49$ $\begin{matrix} 8 \\ 6 \\ 1 \end{matrix}$ $|C_{ah}^{\text{eff}}| = 0.1$, $\text{Br}(a \to e^+e^-) > 0.049$ $|C_{ah}^{\text{eff}}| = 1$, $Br(a \to e^+e^-) > 0.006$ **Beam** $\mathbf{1}$ $rac{4x}{4}$ (for $\Lambda = 1 \text{ TeV}$) Edelweiss 10^{-3} λ_{λ} Assume (absence of LFV transitions): $c_{ee} \approx c_{\mu\mu} \approx c_{\tau\tau}$ **Red Giants** $h \rightarrow aa$ 10^{-6} 10^{-9} 10^{-6} 10^{-3} 1 m_a [GeV]

Figure 19: Constraints on the ALP mass and coupling to leptons derived from various experiments M. Neubert: Recent progress on ALPs (La Thuile 2019) 12

Probing the ALP-photon coupling

- Alternative representation of the parameter space in the ALP-Higgs and ALP-photon coupling plane
- Accessible region depends on the ALP mass and $a \rightarrow \gamma \gamma$ branching ratio (dashed contours)
- Lines show predictions for the coefficients in two scenarios with couplings induced by loops of SM fermions

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Probing ALPs at Future Colliders

❖ We focus on ALP decay *a*→*γγ* but similar results hold for ALP decays into leptons, jets or heavy quarks

ALP searches at future hadron colliders

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ALP searches at future e⁺e-colliders

Figure 5.5.: Feynman diagrams contributing to the process *e* (assuming *CWW*=0, so that *Cγγ* and *CγZ* are correlated)

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ALP searches at future e⁺e-colliders

based on work with Mathias Heiles **e**s 11. *e* 11. **e** H_2 *pp* 27 15 H_2 27 16 H_2

assumes $Br(a \rightarrow \gamma\gamma) = 1$.

Conclusions

- ❖ Exotic Higgs and Z decays provide new probes for ALPs with masses between 1 MeV and 90 GeV, and couplings suppressed by Λ~1-100 TeV and beyond
- Searches for final states such as $h \to 4\gamma$, $h \to \ell^+ \ell^- \gamma \gamma$, $h \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$ and final states with jets need to be devised 2
- ❖ Accessible parameter space could be significantly enlarged at future hadron and lepton colliders

