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## Axion-Like Particles @ Colliders

M. Bauer, MN, A. Thamm: 1704.08207 (PRL), 1708.00443 (JHEP) M. Bauer, MN, S. Renner, M. Schnubel, A. Thamm: 2012.12272 (JHEP), 2102.13112 (PRL), 2110.10698 (JHEP) C. Cornella, A. Galda, MN, D. Wyler: 2308.16903



### **Increasing mass**

## **Terra incognita**

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### **Searches for heavy particles with large couplings**



### **Increasing mass**

## **Terra incognita**

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## **Searches for heavy particles with**



### **Increasing mass**

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### **Increasing mass**

### opeless SMI Hopeless SMEFT

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## SMEFT **large couplings**

coupling **Decreasing coupling** ecreasing



### **Increasing mass**

### **SM + X** light **particles with small**

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## **new Particles Bulled**<br> **Expedience** Ruled out

## SMEFT **large couplings**

### opeless SMI SM + X<sub>light</sub> Hopeless SMEFT

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### Well motivated theoretically:

- Peccei—Quinn solution to strong CP problem: new scalar field  $\Phi = |\Phi| \, e^{\, i a/f_a}$  coupled to chiral fermions, charged under a symmetry  $U(1)_{PQ}$ *a* [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]
- Spontaneous symmetry breaking yields a VEV for  $\Phi$
- Performing a chiral transformation on the fermion fields, one finds:

2

$$
\mathcal{L}_{\text{QCD}} \rightarrow \left(\theta + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} + \ldots
$$





### Well motivated theoretically:

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• Peccei—Quinn solution to strong CP problem: new scalar field  $\Phi = |\Phi| \, e^{\, i a/f_a}$  coupled to *a* [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]



• QCD instantons generate a potential for the axion and enforce  $\theta_{\text{eff}}=0$  mod 2π



2

$$
\mathcal{L}_{\text{QCD}} \rightarrow \left(\theta + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} + \ldots
$$

### Well motivated theoretically:

• Axion mass is inversely proportional to $f_a$  and can be very light if  $f_a$  is sufficiently large:

• Axion coupling to photons is also inversely proportional to  $f_a$  with a model-dependent coefficient

$$
m_a^2 f_a^2 = \frac{m_\pi^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2}
$$

[Kim 1979; Shifman, Vainshtein, Zakharov 1980 (KSVZ)] [Dine, Fishler, Srednicki 1981; Zhitnitsky 1980 (DFSZ)]





• More generally, axion-like particles (ALPs) can arise as pseudo Nambu—Golstone bosons

• For heavier ALPs, couplings to SM particles other than the photon play an important role

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## Well motivated theoretically:

- [for recent ideas, see e.g.: Elahi, Elor, Kivel, Laux, Najjari, Yu 2023; Gavela, Quílez, Ramos 2023]
- of a spontaneously broken global U(1) symmetry in a large class of BSM models
- and can be probed in particle-physics experiments [Bauer, MN, Thamm 2017; …]

• There are ways to relax the strict relation between the axion mass and photon coupling

## Effective Lagrangian for a light ALP

- All interactions are suppressed by inverse powers of  $f$  , with  $f/|2c_{GG}| = f_a$ • 5 out of the 49 real couplings in this Lagrangian are redundant
- 
- 

 $\blacktriangledown$ *F*  $\bar{\psi}_F c_F \gamma_\mu \psi_F + c_\phi$  $\partial^{\tilde{\mu}}a$ *f*  $\overline{(\ }$  $\phi^\dagger i\overleftrightarrow{\bm D}_\mu \phi\big)$  $\alpha_2$  $4\pi$ *a*  $\frac{d}{f} \, W_{\mu\nu}^A \, \tilde{W}^{\mu\nu,A} + c_{BB}$  $\alpha_1$  $4\pi$ *a*  $\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$ couplings to chiral fermions coupling to Higgs doublet  $\overline{\mathcal{L}}$  coupling to hypercharge bosons coupling to hypercharge boson

• Will always work with physical combinations  $\tilde{c}_{VV}^{\phantom{\dag}}, c_{qq}^a$  of coupling parameters



• Most general effective Lagrangian for a pseudoscalar boson  $\boldsymbol{a}$  coupled to the SM via classically shift-invariant interactions (broken softly by a mass term): [Georgi, Kaplan, Randall 1986]

$$
\mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} \left( \partial_{\mu} a \right) \left( \partial^{\mu} a \right) - \frac{m_a^2}{2} a^2 + \frac{\partial^{\mu} a}{f}
$$
  
coupling to gluons  

$$
+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW}
$$



## RG evolution from the UV to lower scales



**Chiral symmetry breaking**  $\Lambda_{\chi} = 4\pi f_{\pi}$ 





### **Peccei-Quinn symmetry breaking**

 $\Lambda = 4\pi f$ 

### **Electroweak symmetry breaking**

 $\sim 100 \,\mathrm{GeV}$ 

[Bauer, MN, Renner, Schnubel, Thamm 2020; Chala, Guedes, Ramos, Santiago 2020]

## High-energy probes of ALP couplings



## ALP production in Higgs-boson decays

Interesting search channel  $h \to aa \to 4\gamma$ 

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[Bauer, MN, Thamm 2017]

 $\overline{7}$ 

## ALP production in Higgs-boson decays



[Bauer, MN, Thamm 2017] 7



## Interesting search channel *h* → *aa* → 4*γ*

- Resulting bounds on the ALP—photon coupling (ALP decay) depend on the ALP coupling  $(\partial_{\mu}a)^{2}\phi^{\dagger}\phi$  to Higgs bosons (ALP production)
- Potential to cover the parameter space in which an ALP could explain (*g*-2)<sup>μ</sup>

Matthias Neubert **La Thuile 2024: Axion-Like Particles @ Colliders**  $\mathcal{F}_1$  is constraint on the ALP mass and coupling to photons derived from various experiments of  $\mathcal{F}_2$ 







[ATLAS collaboration, arXiv:2312.03306]  $F_{\text{MLE}}$  mass and conduction, and  $F_{\text{MLE}}$  and  $F_{\text{MLE}}$  (1,  $F_{\text{MLE}}$  , 1,  $F_{\text{MLE}}$  with  $F_{\text{MLE}}$ 

## Interesting search channel *h* → *aa* → 4*γ*

- Resulting bounds on the ALP—photon coupling (ALP decay) depend on the ALP coupling  $(\partial_{\mu}a)^{2}\phi^{\dagger}\phi$  to Higgs bosons (ALP production)
- Potential to cover the parameter space in which an ALP could explain (*g*-2)<sup>μ</sup>
- Recent ATLAS analysis confirms our estimates

Matthias Neubert La Thuile 2024: Axion-Like Particles @ Colliders dia das hed lines as predicted in Ref. [19]. The shaded in Ref. [19]. The shaded blue area represents the shaded blue area rep



## Flavor probes of ALP couplings

### Interesting search channel **K**<br>Katha<del>rixh Mas(</del> and *k <sup>Q</sup>* ! *U<sup>L</sup> k <sup>Q</sup> U† <sup>L</sup>*. Applying the Noether procedure serich chack and method meson the  $H$ ak sounting for an analiting the the factor is herippin the **performed in 1981. The** to the Lagrangians hat the measures, as stind to the captile accounting for an additional phase factor and promotion ch holl hot at the fields, we find that the handed that the find that the control of the left  $\alpha$ the little gey file the declaration in which which

- Model-independent analysis using chiral rotation of perturbation theory  $\frac{d}{dx}$  in the later capital conduction  $q_L \gamma_\mu q_L^r$  must be represented  $k_q(\mu_k)$   $]_K$  20 • Model-independent analysis using chiral  $\mathsf{H}^{\mathsf{H}}$  and  $\mathsf{H}^{\mathsf{H}}$  and  $\mathsf{H}^{\mathsf{H}}$  and  $\mathsf{H}^{\mathsf{H}}$  in  $\mathsf{H}^{\mathsf{H}}$ for physical observables. For  $i f^2$   $i(t_0 - i t_0 + i s_0)$  possible to choose the ahisal releative currents is using criminal situation of the chiral situation  $\bm{k}_Q(\mu_\chi) - \bm{k}_q(\mu_\chi)$ theory by onnativation of vere vergosspecters every detailed the o IVIOUUFI-II IUTOTI IUTITU ULIUPYSIS USILIY CITII ULIUPI III ON III ON III ULIUPI III ON IIII ON IIII ON IIII for perturbation theory for  $\Pr\left[k_Q(\mu_\chi)-k_Q\right]$  $\frac{1}{4}$  (*µ*) *k*<sup>0</sup> *k*<sup>0</sup>
- Previous calculations used an incorrect implementation of the chiral currents; as a result, the BR gets enhanced by factor 37 ⇡ <sup>4</sup> *<sup>e</sup>*  $i$ s used ar ⌃ (*Dµ*⌃) • Previous colculations used an incorrect that matrix in this case, the 0tion<br>2 *D* an  $\frac{1}{\pi}$ **of the chiligh strents; as a**  $\frac{1}{2} + i\frac{1}{2} - i\frac{1}{2}$ result, the BR gets enhanced by factor 37.  $\overline{\partial^{\mu}_{f}a}$  $\frac{1}{2}$  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  the  $\frac{1}{2}$  the  $\frac{1}{2}$   $\frac$  $t_{\rm eff}$   $t_{\rm eff}$   $\frac{1}{2}$   $\frac$ a way that *k* ˆ **q** such the *k* ˆ  $L^{ji} = \frac{if_{\pi}^2}{\sqrt{if_{\pi}^2}}$ *e*<br>106  $\frac{1}{q_i} \frac{1}{\dot{q}_i} \frac{\omega}{q_i}$  $\frac{45}{9}$  *d*/ $\frac{45}{9}$  $\mathbf{F}_{\mathbf{p}}\left(\mathbf{D}_{\mathbf{p}}\mathbf{D}_{\mathbf{p}}\right)$ *†*⇤*ji*  $\frac{1}{2}$  dtic $\frac{1}{2}$  $\overline{z}$  $\frac{1}{4}$ F 1 + *i*(*<sup>q</sup><sup>i</sup> <sup>q</sup><sup>j</sup> <sup>q</sup><sup>i</sup>* + *<sup>q</sup><sup>j</sup>* ) *cGG a f* ⇥ In (7) the ALP enters in the quark mass matrix *m* ˆ *<sup>q</sup>*(*a*) <sup>+</sup> *<sup>f</sup>* <sup>2</sup> ⇡ @*<sup>µ</sup>a* ⇥ ˆ ˆ *<sup>q</sup>* ⌃*†*⇤*ji .* (13) *k* **Q WOO K**  $L^{ji} = -\frac{if_n^2}{i^2}e^{i(\phi_{q_i}^-\frac{1}{i}\phi_{q_i}^+)}$  appsible to choose the **•** Previous calculations used an inc  $\frac{1}{2} - \frac{1}{2} - \frac{1$ **the very special situation in the very set of the very set of** ˆ **q** and **q**  $\hat{\vec{k}}$
- Strong constraints on flavor-violating and flavor-conserving ALP couplings and derivative  $+\frac{f_{\rm F}^2}{4}$  $\mathbf{F}% _{0}$ 4 *f* ⇥ *k*  $\hat{\vec{k}}$ **Of KONG 42**  $\mathcal{H}_{q}^{q}$  **here** the tuning to realize this JUI<br>Cr **k** a construct of a control construction of the equation of t יי<br>∍ו constraints on flaver viol  $\overline{4}$ *f* This generates both mon-derivative and derivative court plits y the C-2 to the With With the weak-interaction vertices.  $\mu$  *k*<br>*k*<br>*k*<br>*k*<br>*k*<br>*k*<br>*k* ے<br>\\  $^{\prime}$ @Eating.and it is possible to choose the matrices *<sup>q</sup>* and *<sup>q</sup>* in such **low te als call** a

Matthias Neubert **La Thuile 2024**: Thuile 2024: Axion-Like Particles @ Colliders plings of the Chure to the weak interaction were over with the special coupling of a power choice can eliminate the green derivative couplings; however, the derivative coupled thes remain. As to tour that the contribution of the contribution of the contribution of the contribution of the co<br>Alp only enters the contribution of the contribution of the contribution of the contribution of the contributio involving the derivative of the ALP field of the derivative merges, in the literature. It has neuther to the literature of the literature of the literature renormalization and it<br>Under renormalization and it has needed to the literature of the literature of the literature of the literatur the special choice  $\frac{1}{2}$  interactions with many *<sup>q</sup>* and *k* 化<br>」 W both vanished water was also been also want to cape the case of Uefivangvalc6uplings; howevener sands imitiate cape finals demant! YA GOUN UIBSL however, the Iderum tive couplings and the charge in the contribution th volu Hiserature in the quark field and field and the meson fields and meson fields transform non-linearly as a line to the equilibrium of early of the extension of the e phenspecial choice to the weak unferaction ivenues with Involving AREQUITIVE OF THE ELATER THE ROOM OF THE BULLOU in the organizing part has not be a make the based of  $\Omega$ pontium speaks hat was contributed to a left-handed, *D*<sup>2</sup> 3 transform non-linearly as ⌃ ! *UL*⌃. The e↵ective La- $\frac{1}{2}$ )e<br>⊾⊆ Clear CHOTCC ARGHT in terreductions and the HOW GIREY REC and described by the BU. invariant under relative of the Ariston education would need a fine tuning to realize the tuning to realize the condition of the condition at the condition at the condition of the conditi 44 fermion operations builty out of products of estimated the products of the contractors of the contractors o tion **particular for the detail of the measurement** of the details fields HGRAHA IS INVARIAN IS INVARIATE UNDER THE WARD IS IN A TRANSFORMATION IN DE

de de dence on the second of the second was least service since and for hos foldel besservabled. For favore and social presidiction **stranstorming as a wather move departules us a the ward was In (10) other has Place (439 the 149 MB and the compact matrix matrix** and this agu sit and four anisherive the covariant defined in (5). For  $K^ \pi^ K^ K^ \pi^ K^-$ **L. A. U. S. LOC. H. L. L. C. Applying the Northern Procedure and Act in Contract of the Northern Processing Co** such as *a* ! and *a* ! ⇡⇡⇡, an analogous study was In (7) the ALP and the second of the second mass mass mass in the mass mass mass of  $\mathbf{a}_i$ and the compact of the conception of the correct in  $\mathcal{G}$ . For a contribution of  $\mathcal{G}$ *A K* denote the final capacity of the considered **!** 

### ALP production in rare kaon decays 4-fermion operators built out of products of left-handed  $\epsilon$ urrents. Under, a defthanded, flavor offrdiagonal fields tion *q<sup>L</sup>* ! *U<sup>L</sup> q<sup>L</sup>* of the quark fields, the meson fields transforms invariage Region as the early as a straight grangian is invariant and smithis anstanding which team  $\frac{1}{2}$  where  $\frac{1}{2}$ 8  $\frac{1}{2}$   $\frac{$ *s<sup>L</sup>* ! *d<sup>L</sup>* transition. We have calculated the *K* ! ⇡*a* und the Feynman graphs of the figure 1.  $\epsilon$ ulef $\epsilon$ nt $\epsilon$ n Under  $\alpha$ sl $\epsilon$ ft-handed, flavor of $\epsilon$  o $t$ al  $\epsilon$ str $\alpha$ landed tion of the quark fields of the control of the meson fields transform the equality as  $\mathbb{Z}^n$ . The equal of the equal to the equal the equal to the equal to  $\mathbb{Z}^n$ grangian is invariant witch to hall and the transition in the transition where  $|g_8| \approx 5.0$  [29], and the index pair "32" signals a  $\frac{1}{2}$   $\$  $d\phi$  and  $d\phi$  and  $1$  and  $d\phi$  $\frac{1}{\sqrt{2}}$  in Figure 1. The figure 1.

## plings as spurions transforming as *m*

couplings, as parameterized by the o↵-diagonal elements *K g*<sup>8</sup> *g*<sup>8</sup> of  $\sigma_{q_{\mathbf{A}}}$ <sup>III</sup> Such  $\sigma_{q_{\mathbf{A}}}$ <sup>1</sup> and  $\sigma_{q_{\mathbf{A}}}$ . The matrices  $\sigma_{q_{\mathbf{A}}}$ . The chiral examplify the analysis of  $\sigma_{q_{\mathbf{A}}}$ . his case, the cay amplicate at reading order in the chirar chiral order to the set  $\frac{1}{2}$  and  $\frac{1}{2}$  and e guess mass.<br>The contribution dots refer to vertices from the Lagrangian (" Fig. 1. FIG. The *K* is called the called the chiral expansion of the chiral expansion of  $\alpha$  is the chiral expansion of  $\alpha$  in  $\alpha$ interaction vertices are indicated by a cros <del>ge</del> uses.<br>the contribution dots refer to vertices from the Lagrangian (7<br>e-contribution ALP-pion prass here interaction vertices are indicated of the matrices **k**<sub>d</sub> and **k**<sup>*x*</sup> in euch **k**<sub>*FIG. 1.* Fevnman graphs contributing to the analysis of an</sub> mas case, the *interaction* vertices are indicated by a cros FIG. 1. Feynman graphs contributing to the  $\text{cay amplitude at leading order in the chiral e}$ dots refer to vertices from the Lagrangian (7).

articles @Collects & CG (dataveamedity dent on the lsast of asidn srig [Bauer, MN, Renner, Schnubel, Thamm 2021] various diagrams. In units of *<sup>N</sup>*<sup>8</sup> <sup>=</sup> *<sup>G</sup>* **EFORCE 2Bam**<br>m: 2Bam<br>**EFORCE** constitute and model into the ቺኒውኮ ያስ<sub>ብረ</sub>ቢ<br>ፈተማሪ የዕመደባር the equations of motion.) The octet ope structive to se huge dynamical enhancement known as also De useu<br>**Briel Ning, the complete of the scheme-dependent contribution** involving the angs. The rest of the corresponding Lagi p FIG. 1. Feynman graphs contributing to the *K* ! ⇡*a* de-*<sup>L</sup>*weak <sup>=</sup> 4*G<sup>F</sup>* with *<sup>|</sup>N*8*<sup>|</sup>* ⇡ <sup>1</sup>*.*<sup>53</sup> *·* <sup>10</sup><sup>7</sup>, we find for these contributions cay amplitude at leading order in the chiral expansion. Weak-*F* **2** *Vd* \*  $\frac{10.006}{10.006}$  are  $\frac{10^{-7}}{10^{10}}$  we find for these contributions pelye df the Aare, flant the Icentrial Lagrangian (1). The Cage of *N*<sup>8</sup>  $\frac{2}{\pi} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \left( \frac{1}{2} \frac{1}{2}$ *D*<sup>2</sup> 3 *N*<sup>8</sup> <sup>6</sup>*<sup>f</sup> <sup>c</sup>GG* (2*m*<sup>2</sup>  $2^{\mu}$ <sup>o</sup>  $\frac{\nu}{\mu}$  $2^{\frac{1}{2}}$   $3^{\frac{1}{2}}$  $2\left(\frac{1}{2} + \frac{1}{2}a + \frac{1}{2}a\right)$ *a a* interaction vertices are indicated by a crossed circle, while  $\mathbb{C}^1$  or  $\mathbb{C}$  of  $\mathbb{C}^1$  of  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$ The kappa dependence reads and ⇡ ! *e*⌫¯*<sup>e</sup> a*, which in the SM are mediated by the to study flavor to study and we have so which as *KATHONS! SLACT* huge dynamical enhancement known as hection rule [28]. The corresponding Lagree lection rule [28]. The corresponding Lagr  $rac{\sqrt{52}}{\sqrt{52}}$  $\frac{1}{2}$   $\sqrt[4]{\det(\mathbf{a})}$  amplitude from  $\mathbf{W}$  and  $\mathbf{B}$   $\mathbf{x}$  grangians (7)  $U_{\alpha\alpha}$  time the Feynman graphs shown in Figure 1. The figure 1. Faas ang tipe afser rigs refer digital page of the control securitori to  $Beta$  are  $g\rho$  and the equations of motion.) The octet operations are  $Beta$ stručtive to se huge dynamical enhancement known as involving the dection rule [28]. **I he coorresponding** Lagi united the diagrams. In the second of the state of the components of the components of the components of the co p.<br>Pr *F* 2 **12 N88**  $N_{\rm B}$ <sup>1</sup> FIG. 1. FEW RUEL LACT AND SAILIN FUILLE TO THE TALL THE WELFALL  $\frac{1}{2}$  in the contribution  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  contribution  $\frac{1}{2}$  of  $\frac{1}{2}$ with  $A$  is easily in the motion of motion  $\mathcal{A}$  and  $\mathcal{A}$  The kappa dependence with the within the control of the control of the control of the control of the control of<br>The called in the control of the control of the control of the control of the within 2021 **and Standard Bandard Conduct in the SMAN are mediated by the SMAN and the SMAN are mediated by the SMAN are me**<br>To the Weak, Micrael Calon, WeithCeb<sub>en</sub> Wathi huge dynamical enhancement known as n (7) can also ope used alection rule [28]. The corresponding Lagr<br>fing Napts and Ming the coupling or all the cancer settle radiation p21  $\mathbf{Y}_{\mathbf{u}}^*$ where  $\left| \begin{array}{c} g_8 \\ g_2 \end{array} \right| \approx 5.0$ , [29], and the index pair  $\frac{1}{2} \sum_{i=1}^{\infty} \frac{d^{2}x}{d^{2}x^{2}}$   $\frac{1}{2} \sum_{i=1}^{\infty} \frac{d^{2}y}{dx^{2}}$   $\frac{1}{2} \sum_{i=1}^{\infty} \frac{d^{2}y}{dx^{2}}$ **ALPRIEFRA** 



₹₩  $\frac{1}{2}$  the contribution from the  $\frac{1}{2}$  superators, will be pre**dr:**<br>Be *K*  $\frac{1}{2}$ *a*  $\frac{1}{2}$  both vanish. In this case, the *a g*8 **Quantificial Papie Hellenger mass**  $A$  on  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$   $\mathbb{C}$   $\mathbb{C}$   $\mathbb{C}$  and  $\mathbb{C}$   $\mathbb{C}$ matrix (8), see the set of the set invariant under renormalization-group experiment and its would need a fine tuning to realize this condition at the ⌃ @*µ*⌃*†*⇤*ji*  $\operatorname{sehr}$  and  $\operatorname{sehr}$  must be meson masses as the meson masses are then given by  $\operatorname{sehr}$ **EFLAY**<br>HIMA **E** DE 2014  $K_{\alpha}^{\text{sp}}$  $\frac{\pi}{\pi}$ senten it is possible to choose the matrices  $\kappa_q$  and  $\delta_{q\blacktriangle}$  in such  $\mathbf{K}$  $\alpha$ *g*8 A Mayonkers the Lagrangian through the Lagrangian  $\mathbf{G}$  is  $\mathbf{G}$  is  $\mathbf{G}$  and  $\mathbf{G}$  and  $\mathbf{G}$  and  $\mathbf{G}$  is not  $\mathbf{G}$  is not  $\mathbf{G}$ invariant under renormalization-group en contemplation and the Woold Need a fine to hand to healise this condition and he VOGEMQICLIHG OILL<sub>angian</sub> (7) can also <sup>be</sup> used to be the study of the such as  $\frac{1}{2}$  is a set of the such as  $\frac{1}{2}$  and  $\frac{1}{2}$  is a set of the such as  $\frac{1}{2}$  and  $\frac{1}{2}$  is a set of  $\frac{1}{2}$  and  $\frac{1}{2$ 





### Interesting search channel **K**<br>Katha<del>rixh Mas(</del> and *k <sup>Q</sup>* ! *U<sup>L</sup> k <sup>Q</sup> U† <sup>L</sup>*. Applying the Noether procedure serich chack and method meson the  $H$ ak sounting for an analiting the the factor is herippin the **performed in 1981. The** to the Lagrangians hat the measures, as stind to the captile accounting for an additional phase factor and promotion ch holl hot at the fields, we find that the handed that the find that the control of the left  $\alpha$ the little gey file the declaration in which which

- Model-independent analysis using chiral rotation of perturbation theory  $\frac{d}{dx}$  in the later capital conduction  $q_L \gamma_\mu q_L^r$  must be represented  $k_q(\mu_k)$   $]_K$  20 • Model-independent analysis using chiral  $\mathsf{H}^{\mathsf{H}}$  and  $\mathsf{H}^{\mathsf{H}}$  and  $\mathsf{H}^{\mathsf{H}}$  and  $\mathsf{H}^{\mathsf{H}}$  in  $\mathsf{H}^{\mathsf{H}}$ for physical observables. For  $i f^2$   $i(t_0 - i t_0 + i s_0)$  possible to choose the ahisal releative currents is using criminal situation of the chiral situation  $\bm{k}_Q(\mu_\chi) - \bm{k}_q(\mu_\chi)$ theory by onnativation of vere vergosspecters every detailed the o IVIOUUFI-II IUTOTI IUTITU ULIUPYSIS USILIY CITII ULIUPI III ON III ON III ULIUPI III ON IIII ON IIII ON IIII for perturbation theory for  $\Pr\left[k_Q(\mu_\chi)-k_Q\right]$  $\frac{1}{4}$  (*µ*) *k*<sup>0</sup> *k*<sup>0</sup>
- Previous calculations used an incorrect implementation of the chiral currents; as a result, the BR gets enhanced by factor 37 ⇡ <sup>4</sup> *<sup>e</sup>*  $i$ s used ar ⌃ (*Dµ*⌃) • Previous colculations used an incorrect that matrix in this case, the 0tion<br>2 *D* an  $\frac{1}{\pi}$ **of the chiligh strents; as a**  $\frac{1}{2} + i\frac{1}{2} - i\frac{1}{2}$ result, the BR gets enhanced by factor 37.  $\overline{\partial^{\mu}_{f}a}$  $\frac{1}{2}$  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  the  $\frac{1}{2}$  the  $\frac{1}{2}$   $\frac$  $t_{\rm eff}$   $t_{\rm eff}$   $\frac{1}{2}$   $\frac$ a way that *k* ˆ **q** such the *k* ˆ  $L^{ji} = \frac{if_{\pi}^2}{\sqrt{if_{\pi}^2}}$ *e*<br>106  $\frac{1}{q_i} \frac{1}{\dot{q}_i} \frac{\omega}{q_i}$  $\frac{45}{9}$  *d*/ $\frac{45}{9}$  $\mathbf{F}_{\mathbf{p}}\left(\mathbf{D}_{\mathbf{p}}\mathbf{D}_{\mathbf{p}}\right)$ *†*⇤*ji*  $\frac{1}{2}$  dtic $\frac{1}{2}$  $\overline{z}$  $\frac{1}{4}$ F 1 + *i*(*<sup>q</sup><sup>i</sup> <sup>q</sup><sup>j</sup> <sup>q</sup><sup>i</sup>* + *<sup>q</sup><sup>j</sup>* ) *cGG a f* ⇥ In (7) the ALP enters in the quark mass matrix *m* ˆ *<sup>q</sup>*(*a*) <sup>+</sup> *<sup>f</sup>* <sup>2</sup> ⇡ @*<sup>µ</sup>a* ⇥ ˆ ˆ *<sup>q</sup>* ⌃*†*⇤*ji .* (13) *k* **Q WOO K**  $L^{ji} = -\frac{if_n^2}{i^2}e^{i(\phi_{q_i}^-\frac{1}{i}\phi_{q_i}^+)}$  appsible to choose the **•** Previous calculations used an inc  $\frac{1}{2} - \frac{1}{2} - \frac{1$ **the very special situation in the very set of the very set of** ˆ **q** and **q**  $\hat{\vec{k}}$
- Strong constraints on flavor-violating and flavor-conserving ALP couplings and derivative  $+\frac{f_{\rm F}^2}{4}$  $\mathbf{F}% _{0}$ 4 *f* ⇥ *k*  $\hat{\vec{k}}$ **Of KONG 42**  $\mathcal{H}_{q}^{q}$  **here** the tuning to realize this JUI<br>Cr **k** a construct of a control construction of the equation of t יי<br>∍ו low scale *µ*. 4 *f* This generates both mon-derivative and derivative court plits y the C-2 to the With With the weak-interaction vertices. con  $\mu$  *k*<br>*k*<br>*k*<br>*k*<br>*k*<br>*k*<br>*k* ے<br>\\  $^{\prime}$ @Eating.and it is possible to choose the matrices *<sup>q</sup>* and *<sup>q</sup>* in such **low te als call** a

Matthias Neubert **La Thuile 2024**: Thuile 2024: Axion-Like Particles @ Colliders the special coupling of a power choice can eliminate the green derivative couplings; however, the derivative coupled thes remain. As to tour that the contribution of the contribution of the contribution of the contribution of the co<br>Alp only enters the contribution of the contribution of the contribution of the contribution of the contributio involving the derivative of the ALP field of the derivative merges, in the literature. It has neuther to the literature of the literature of the literature renormalization and it<br>Under renormalization and it has needed to the literature of the literature of the literature of the literatur the special choice  $\frac{1}{2}$  interactions with many *<sup>q</sup>* and *k* 化<br>」 W both vanished water was also been also want to cape the case of Uefivangvalc6uplings; howevener sands imitiate cape finals demant! YA GOUN UIBSL however, the Iderum tive couplings and the charge in the contribution th volu Hiserature in the quark field and field and the meson fields and meson fields transform non-linearly as a line to the equilibrium of early of the extension of the e phenspecial choice to the weak unferaction ivenues with Involving AREQUITIVE OF THE ELATER THE ROOM OF THE BULLOU in the organizing part has not be a make the based of  $\Omega$ *D*<sup>2</sup> 3 transform non-linearly as ⌃ ! *UL*⌃. The e↵ective La- $\frac{1}{2}$ )e<br>⊾⊆ Clear CHOTCC ARGHT in terreductions and the HOW GIREY REC and described by the BU. invariant under relative of the Ariston education would need a fine tuning to realize the tuning to realize the condition of the condition at the condition at the condition of the conditi HGRAHAR IS INVARIANT UNDER THE TRANSFORMATION IS IN THE TRANSFORMATION IN THE TRANSFORMATION IS A LIMITED OF T

two disguished  $\begin{picture}(180,10) \put(0,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line(1,0$ but interpretations  $\pi^0$ .  $\mathbf{u}_i$ the  $\mathbf{u}_i$  interactions  $\mathbf{u}_i$ **(13). The following two graphs described and the following description of the following description of the following description of the following description of the following design design design design design design desi** an  $K^ K^ \pi^ K^ K^ \pi^$ de de dence on the second of the second was least service since and for hos foldel besservabled. For favore and social prosidents **stranstorming as a wather move departules us a departule was allowed was also as a complete In (10) other has Place (439 the 149 MB and the compact matrix matrix** and this agu sit and four anisherive the covariant defined in (5). For  $K^ \pi^ K^ K^ \pi^ K^ \begin{CD} \text{BMS} \rightarrow \infty \qquad \qquad \text{or} \qquad \qquad$  $\pi^0$  interactions at the weak vertex derived from  $\eta$  in  $\ldots$ (13). The following two graphs of the following two graphs  $a$ an interference meson. They give nonzero contributions if  $K^ \otimes$   $\overline{\phantom{K^-}}$   $\otimes$   $\overline{\phantom{K^-}}$   $\otimes$   $\overline{\phantom{K^-}}$   $\otimes$   $\overline{\phantom{K^-}}$ such as *a* ! and *a* ! ⇡⇡⇡, an analogous study was In (7) the ALP and the second of the second mass mass mass in the mass mass mass of  $\mathbf{a}_i$ and the compact of the conception of the correct in  $\mathcal{G}$ . For a contribution of  $\mathcal{G}$ *A K* denote the final capacity of the considered **!**  $\bigotimes_{\mathbb{R}} \longrightarrow \bigotimes_{\mathbb{R}} \longrightarrow \bigotimes_{\mathbb{R}} \longrightarrow \bigotimes_{\mathbb{R}} \longrightarrow \bigotimes_{\mathbb{R}}$ 

### ALP production in rare kaon decays 4-fermion operators built out of products of left-handed  $\epsilon$ urrents. Under, a defthanded, flavor offrdiagonal fields tion *q<sup>L</sup>* ! *U<sup>L</sup> q<sup>L</sup>* of the quark fields, the meson fields transforms invariage Region as the early as a straight grangian is invariant and smithis anstanding which team  $\frac{1}{2}$  where  $\frac{1}{2}$ 8  $\frac{1}{2}$   $\frac{$ *s<sup>L</sup>* ! *d<sup>L</sup>* transition. We have calculated the *K* ! ⇡*a*  $\pi^{-}$ und the Feynman graphs of the figure 1.  $\epsilon$ ulef $\epsilon$ nt $\epsilon$ n Under  $\alpha$ sl $\epsilon$ ft-handed, flavor of $\epsilon$  o $t$ al  $\epsilon$ str $\alpha$ landed tion of the quark fields of the control of the meson fields transform the equality as  $\mathbb{Z}^n$ . The equal of the equal to the equal the equal to the equal to  $\mathbb{Z}^n$ grangian is invariant witch to hall and the transition in the transition where  $|g_8| \approx 5.0$  [29], and the index pair "32" signals a  $\frac{1}{2}$   $\$  $d\phi$  and  $d\phi$  and  $1$  and  $d\phi$  $\frac{1}{\sqrt{2}}$  in Figure 1. The figure 1.  $\mathbf{w}$  and  $\mathbf{w}$  and  $\mathbf{w}$  and  $\mathbf{w}$  and  $\mathbf{w}$

### plings as spurions transforming as *m* **L. A. U. S. LOC. H. L. L. C. Applying the Northern Procedure and Act in Contract of the Northern Processing Co**

couplings, as parameterized by the o↵-diagonal elements *K g*<sup>8</sup> *g*<sup>8</sup> of  $\sigma_{q_{\mathbf{A}}}$ <sup>III</sup> Such  $\sigma_{q_{\mathbf{A}}}$ <sup>1</sup> and  $\sigma_{q_{\mathbf{A}}}$ . The matrices  $\sigma_{q_{\mathbf{A}}}$ . The chiral examplify the analysis of  $\sigma_{q_{\mathbf{A}}}$ . his case, the cay amplicate at reading order in the chirar chiral order to the set  $\frac{1}{2}$  and  $\frac{1}{2}$  and e guess mass.<br>The contribution dots refer to vertices from the Lagrangian (" Fig. 1. FIG. The *K* is called the called the chiral expansion of the chiral expansion of  $\alpha$  is the chiral expansion of  $\alpha$  in  $\alpha$ interaction vertices are indicated by a cros <del>ge</del> uses.<br>the contribution dots refer to vertices from the Lagrangian (7<br>e-contribution ALP-pion prass here interaction vertices are indicated of the matrices **k**<sub>d</sub> and **k**<sup>*x*</sup> in euch **k**<sub>*FIG. 1.* Fevnman graphs contributing to the analysis of an</sub> mas case, the *interaction* vertices are indicated by a cros FIG. 1. Feynman graphs contributing to the  $\text{cay amplitude at leading order in the chiral e}$ dots refer to vertices from the Lagrangian (7).

*g*8

⇡ ⇡

*a*

articles @Collects & CG (dataveamedity dent on the lsast of asidn srig [Bauer, MN, Renner, Schnubel, Thamm 2021] various diagrams. In units of *<sup>N</sup>*<sup>8</sup> <sup>=</sup> *<sup>G</sup>* plings of the Chure to the weak interaction were over with sented elsewhere.) The meson masses are then given by *K K* ⇡ *K <sup>K</sup>* = *B*<sup>0</sup> (*ms*+ ¯*m*), and 3*m*<sup>2</sup> ⌘ = 4*m*<sup>2</sup> *<sup>K</sup> m*<sup>2</sup> ⇡. *g*8 octet operator can be transformed into the first one using ቺኒውኮ ያስ<sub>ብረ</sub>ቢ<br>ፈተማሪ የዕመደባር the equations of motion.) The octet ope result at the resulting decay amplitude in a structure to se in huge dynamical enhancement known as also De useu<br>**Briel Ning, the complete of the scheme-dependent contribution** involving the angs. The rest of the corresponding Lagi p FIG. 1. Feynman graphs contributing to the *K* ! ⇡*a* de-*<sup>L</sup>*weak <sup>=</sup> 4*G<sup>F</sup>* with *<sup>|</sup>N*8*<sup>|</sup>* ⇡ <sup>1</sup>*.*<sup>53</sup> *·* <sup>10</sup><sup>7</sup>, we find for these contributions cay amplitude at leading order in the chiral expansion. Weak-*F* **2** *Vd* \*  $\frac{10.006}{10.006}$  are  $\frac{10^{-7}}{10^{10}}$  we find for these contributions pelye df the Aare, flant the Icentrial Lagrangian (1). The Cage of *N*<sup>8</sup>  $\frac{2}{\pi} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \left( \frac{1}{2} \frac{1}{2}$ *D*<sup>2</sup> 3 *N*<sup>8</sup> <sup>6</sup>*<sup>f</sup> <sup>c</sup>GG* (2*m*<sup>2</sup>  $2^{\mu}$ <sup>o</sup>  $\frac{\nu}{\mu}$  $2^{\frac{1}{2}}$   $3^{\frac{1}{2}}$ *a a* interaction vertices are indicated by a crossed circle, while  $\mathbb{C}^1$  or  $\mathbb{C}$  of  $\mathbb{C}^1$  of  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$  on  $\mathbb{C}^1$ The kappa dependence reads and ⇡ ! *e*⌫¯*<sup>e</sup> a*, which in the SM are mediated by the invariant under renormalization-group experiment and its would need a fine tuning to realize this condition at the to study flavor to study and we have so which as *KATHONS! SLACT* hection rule [28]. The corresponding Lagree lease ansortion as read in a lection rule and the course secondom process of the corresponding Lagr  $rac{\sqrt{52}}{\sqrt{52}}$  $\frac{1}{2}$   $\sqrt[4]{\det(\mathbf{a})}$  amplitude from  $\mathbf{W}$  and  $\mathbf{B}$   $\mathbf{x}$  grangians (7)  $\frac{1}{\mathrm{sept}}$ **E** DE 2014  $Beta$  are  $\epsilon$  the equations of motion.) The octet operations  $\epsilon$ stručtive to se huge dynamical enhancement known as involving the dection rule [28]. **I he coorresponding** Lagi united the diagrams. In the second of the state of the components of the components of the components of the co p.<br>Pr *F* 2 **12** pontium speaks hat was contributed to a left-handed, **N88**  $N_{\rm B}$ <sup>1</sup>  $\mathbf{K}$ FIG. 1. FEW RUEL LACT AND SAILIN FUILLE TO THE TALL THE WELFALL  $\frac{1}{2}$  in the contribution  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  contribution  $\frac{1}{2}$  of  $\frac{1}{2}$ The kappa dependence with the within the control of the control of the control of the control of the control of<br>The called in the control of the control of the control of the control of the within 2021 invariant under renormalization-group en contemplation and the Woold Need a fine to hand to healise this condition and he VOGEMQICLIHG OILL<sub>angian</sub> (7) can also <sup>be</sup> used to be the study of the such as  $\frac{1}{2}$  is a set of the such as  $\frac{1}{2}$  and  $\frac{1}{2}$  is a set of the such as  $\frac{1}{2}$  and  $\frac{1}{2}$  is a set of  $\frac{1}{2}$  and  $\frac{1}{2$ **and Standard Bandard Conduct in the SMAN are mediated by the SMAN and the SMAN are mediated by the SMAN are me**<br>To the Weak, Micrael Calon, WeithCeb<sub>en</sub> Wathi 44 fermion operations builty out of products of estimated the products of the contractors of the contractors o tion **particular for the detail of the measurement** of the details fields huge dynamical enhancement known as n (7) can also ope used alection rule [28]. The corresponding Lagr<br>fing Napts and Ming the coupling or all the cancer settle radiation p21  $\mathbf{Y}_{\mathbf{u}}^*$ where  $\left| \begin{array}{c} g_8 \\ g_2 \end{array} \right| \approx 5.0$ , [29], and the index pair  $\frac{1}{2} \sum_{i=1}^{\infty} \frac{d^{2}x}{d^{2}x^{2}}$   $\frac{1}{2} \sum_{i=1}^{\infty} \frac{d^{2}y}{dx^{2}}$   $\frac{1}{2} \sum_{i=1}^{\infty} \frac{d^{2}y}{dx^{2}}$ **ALPRIEFRA** 

*K*



₹₩  $\frac{1}{2}$  the contribution from the  $\frac{1}{2}$  superiors, with pre**dr:**<br>Be *K*  $\frac{1}{2}$ *a*  $\frac{1}{2}$  both vanish. In this case, the *a g*8 **Quantificial Papie Hellenger mass**  $A$  on  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$  and  $\mathbb{C}$   $\mathbb{C}$   $\mathbb{C}$   $\mathbb{C}$  and  $\mathbb{C}$   $\mathbb{C}$ matrix (8), see the set of the set ⌃ @*µ*⌃*†*⇤*ji* **EFLAY**<br>HIMA  $K_{\alpha}^{\text{sp}}$  $\frac{\pi}{\pi}$ senten it is possible to choose the matrices  $\kappa_q$  and  $\delta_{q\blacktriangle}$  in such  $\alpha$ *g*8 A Mayonkers the Lagrangian through the Lagrangian through  $\mathbf{G}$  is  $\mathbf{G}$  is  $\mathbf{G}$  and  $\mathbf{G}$  and  $\mathbf{G}$  and  $\mathbf{G}$  is not  $\mathbf{G}$  is not  $\mathbf{G}$ 



*g*8

 $\ddot{\phantom{0}}$ 

 $\pi^0$ 

*a*

 $\pi^ \pi^-$ 

*g*8

 $K^-$ 

 $K^-$ 

*a*

 $K^-$ 

 $K^-$ 

*g*8

 $\eta$ 

### the coefficiant the maching result  $k_D(\tilde{\mu}_w^{\vee})$ *ij*  $\frac{15}{11}$ ,  $\frac{11}{20}$ ,  $\frac{1}{1}$  the UN (BCA) d dh<br>straa  $V^*$   $V^*$   $\overline{V^*}$   $V^*$   $\overline{V^*}$   $V^*$   $\overline{V^*}$   $V^*$   $\overline{V^*}$   $\overline{V^*}$ ˆ ⇤ *ij ,*  $\mathcal{H}\mathcal{B}$ (*µ*)) $\mathcal{B}_{ij}$  result be found in eq. (5.7) of evolution functions, ALP couplings to any SM field at the UN scale will at produce here produced yields and contributions to favor-changing down-type  $b$  dow the electroweak scale. We will hake use of the important point in Section  $\epsilon$ new constraints on individual ALP couplings defined at the UV scale, by

# ALP production in rare kaon decays

### Interesting search channel  $K^ \rightarrow \pi^-a$

- ALP flavor violation can arise from the UV theory and/or from the SM **ettiv**is
- Assuming flavor universality in the UV and individual ALP  $\frac{\alpha_t(\mu_m)}{\alpha_t(\mu_m)}$  and  $\frac{\mu_n}{\alpha_t}$  the UV scale, by calculating the UV sc  $f = 1$  TeV yields in the mass basis:

[Bauer, MN, Renner, Schnubel, Thamm 2021] Assuming MFV (92 Yiftandy) for flavor effects to leading logarithmic approximation via these equations. The above results simplify significantly if the  $3\pi$  P. Lagrangian at the  $\ln$   $\chi$  sqale the principle of minimal flavor violation  $[?]$ . Ope shell finds that  $[?]$ ARE  $\sum_{i=1}^{n}$ *m*<sup>2</sup> *t*  $\sum_{\mathbf{v}}$  $\frac{100}{1000}$ 2⇡*s*<sup>2</sup> *w*  $\tilde{c}_W$ W<sub>D</sub>  $f_3$   $\pi$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ 

 $ij$  $\frac{1}{2} \sum_{i=1}^{N} k_i \ln \left( \log_{w} \right)$ )<br>小 *ij*  $i$ eit kø (uti) ⇤  $i\overline{j}$  $\frac{1}{2}$   $\$  $\overline{\mathrm{u}}$  $ij$  $\frac{1}{2}$   $m_{W}^{2}[k_{w}^{T}]\log_{w}\frac{1}{2}$  is the explicit  $k_{w}^{T}$  ( $\frac{1}{2}$   $\frac{1}{$ the ALP couplings  $c_{tt}$  and  $\ddot{\tilde{c}}_{VV}$ . For the reference scale  $f = 1 \text{ TeV}$ , one finds

 $c_{tt}(\mu_w)$ 

 $(1)$ 

 $\stackrel{\mathcal{J}}{m_t^2}$ *t*

9

2

 $\ln \frac{\mu^2_y}{2}$ 

 $\overline{w}$ 

 $\frac{-1}{4}$ 

 $\frac{1}{4}-\frac{3}{2}$ 

2

while the matching contribution  $\Delta$  $\hat{\Delta}$  $k_D(\mu_w)$ *jij* can be found in eq. (5.7) of [? evolution functions,  $A_{\mu}P_{\mu}$  couplings to any SM field at the UV scale will, at some produce logarithmically-enhanced contributions (Ma<sub>tym</sub> ) and type quark couplings down-type qua below the electroweak scale. We will make use of this important point in Section ⇥ *kD*(*µw*)  $\lim_{k\to\infty}\frac{1}{k}\left[\frac{k}{2}k\right]$ *ij*  $\big\{$ *i* SM Reld at the ⇢  $\boldsymbol{\theta}$  $\begin{bmatrix} a \Lambda \\ b \end{bmatrix}$   $\begin{bmatrix} a \Lambda \\ c \end{bmatrix}$   $\begin{bmatrix} a \Lambda \\ d \end{bmatrix}$   $\begin{bmatrix} a \Lambda \\ d \end{bmatrix}$   $\begin{bmatrix} a \Lambda \\ d \end{bmatrix}$ +  $\alpha_t(\mu_{\nu})$ Կե<br>| *ctt*(*µw*)  $\frac{115}{11}$  $\mu_i$ 11 $\mu_i$ <br>**ht** *w*  $\frac{1}{1}$   $\frac{1}{3}$ *a*  $d_j$  **d**<sup>*j*</sup> **d**<sub>*j*</sub> **d** *d*<sub>*j*</sub> **d** *d*<sub>*d*</sub> *d*<sub>*d*</sub> *d*<sub>*d*</sub> *d*<sub>*d*</sub> *d*<sub>*d*</sub> *d*<sub>*d*</sub> *d*<sub>*d*</sub> *d*<sub>*d*</sub>  $\mathcal{U}^{\mathsf{t}}_i$ *t*  $d_i$ *t*



$$
[k_{U,E}(m_t)]_{ij} = [k_{u,d,e}(m_t)]_{ij} = 0
$$

$$
[k_D(m_t)]_{ij} \simeq 0.019 V_{ti}^* V_{tj} \left[ c_{tt}(\Lambda)^{-1} \right].
$$

flavor change through SM loops containing *W*-bosons 6  $I_t(\mu_w, \Lambda)$  $c_{tt}(\delta t) \stackrel{\circ}{=} 0.0032 \, \tilde{c}_{GG}(\Lambda) - 0.0057 \, \tilde{c}_{W}$ 

 $\overline{\phantom{a}}$ 

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 $\mathbb{F}$  evolution functions  $U(p_w, X)$  and  $T_t(\mu_w, X)$  are defined as  $T$  . The above results simplify significantly if the ALP Lagrangian at the UV where the evolution functions  $U(\mu_w, \Lambda)$  and  $T_t(\mu_w, \Lambda)$  are defined as  $U^{\mu}(\mu_w,\Lambda) =$  $\mathrm{i} \hat{\mathbf{m}}^{\mu_{\mathrm{w}}}$ flavor effects to leading logarithmic approximation via these equations. The above results simplify significantly if the ALP Lagrangian at the UV the principle of minimal devertional control. One then finds that  $\lvert \cdot \rvert$ 

### $\frac{\partial \Psi}{\partial q}$ ,  $\frac{\partial \Psi}{\partial r}$  $k_u^{\nu}(t_w)$  $\left[k_U(\mu_w)!\right]_{ij}=\left[k_d(\mu_w)\right]_{ij}=\left[k_d(\mu_w)\right]_{ij}=\left[k_E(\mu_w)\right]_{ij}\stackrel{\text{out}}{=} \left[k_e(\mu_w)\right]_{ij}$

### ⇥ *kD*(*µw*)  $GG(\Delta)_{k,D}$ ⇤  $\frac{\partial \mathbf{V} \cdot \mathbf{V}}{\partial \mathbf{V}} = \frac{\partial \mathbf{V}}{\partial \mathbf{V}} \mathbf{V} + \frac{\partial \mathbf{V}}{\partial \mathbf{V}}$  $W\left(\frac{\Lambda}{\Lambda}\right)$  $c_{tt}(\Lambda)=0.0032\,\tilde{c}_{GG}(\Lambda) - 0.0057\,\tilde{c}_{WW}(\Lambda)$ i

 $\alpha_t(\mu_w)$ 

 $+$ 

**Important subtlety:** a new SU(3) octet operator arises in the LO weak chiral Lagrangian

11

[Cornella, Galda, MN 2023]

 $F^2$ 8  $H_0$   $(D_\mu \theta)(D^\mu \theta)$ 

i  $+$  h.c.

 $D_\mu \theta = -2\tilde{c}_{GG} (\partial_\mu a)/f$  $\Sigma(x) = e^{-\frac{i}{2}\theta(x)\,\kappa_q}\,\Sigma_0(x)\,e^{-\frac{i}{2}\theta(x)\,\kappa_q}$  $L_\mu = \Sigma\,i$  $(D_\mu \Sigma^\dagger)$ 



$$
\mathcal{L}_{\text{QCD}}^{(p^2)} = \frac{F^2}{8} \langle (D_\mu \Sigma) (D^\mu \Sigma^\dagger) + \chi \Sigma^\dagger + \Sigma \chi^\dagger \rangle +
$$
  

$$
\mathcal{L}_{\text{weak}}^{(p^2)} = \frac{F^4}{4} \left[ G_8 \langle \lambda_6 L_\mu L^\mu \rangle + G_8^\theta (D_\mu \theta) \langle \lambda_6 L^\mu \rangle \right]
$$

**Important subtlety:** a new SU(3) octet operator arises in the LO weak chiral Lagrangian

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• will vary it later within reasonable limits

$$
\mathcal{L}_{\text{QCD}}^{(p^2)} = \frac{F^2}{8} \langle (D_\mu \Sigma) (D^\mu \Sigma^\dagger) + \chi \Sigma^\dagger + \Sigma \chi^\dagger \rangle +
$$
  

$$
\mathcal{L}_{\text{weak}}^{(p^2)} = \frac{F^4}{4} \left[ G_8 \langle \lambda_6 L_\mu L^\mu \rangle + G_8^\theta (D_\mu \theta) \langle \lambda_6 L^\mu \rangle \right]
$$

Whereas  $G_8$  is known from  $K \to \pi \pi$  decays,  $G_8^\theta$  is still unknown  $G_8$ 



Diagrams involving flavor-changing ALP couplings:

Matthias Neubert La Thuile 2024: Axion-Like Particles @ Colliders which according to Table 2024: Axion-Like Particles @ Colliders<br>*F*  $\alpha$ Note that this is a finite renormalization, and the scale dependence on the right-hand

### Interesting search channel  $K^ \rightarrow \pi^- a$

- At NLO in chiral perturbation theory the calculation is far more involved
- NLO QCD and weak chiral Lagrangians ( )  $\overline{\mathbb{T}_4}$  $\theta$  **b**  $\theta$  *βμ* $\theta$  *a*  $\theta$  *a*  $\theta$  *a*  $\mathbb{R}^n$  is represented by a dashed line. The ALP is represented by a dashed line. The black square denotes and  $\mathbb{R}^n$ need to be supplemented by 3 resp. 9
- *refers to a vertex from the vertex from the series from the series of the series of the series of the series*  $\mathsf{TS}(\mathsf{C})$  the relevant low-energy constants collected in Table 2.3, the values obtained in Table 2.3, the values obtained in Table 2.3, the values of  $\mathsf{S}(\mathsf{C})$ • Sensitivity to several poorly known lowenergy constants

 $\rm T_5$ 



in (2.18), while the empty square  $\sim$  [Cornella, Galda, MN 2023] where  $\mathcal{A}^{\text{max}}$  and  $\mathcal{A}^{\text{max}}$  is the formatted result. In the formatted result  $\mathcal{A}^{\text{max}}$ 

$$
i{\cal A}^{\rm FV}_{\rm LO+NLO} = -(m_K^2-m_\pi^2)\,\frac{[k_d+k_D]_{12}}{2f}\,F_0^{K\to\pi}(q^2=m_a^2)\,;
$$

*F*⇡  $\hat{q}$ <sup>-</sup>  $=$   $m^2$  $\imath_{a}$ + 2*m*<sup>2</sup> ⇡ ln *<sup>µ</sup>*<sup>2</sup>

 $r_0^2$  (0) = (1 <sup>D</sup>O –  $\frac{F}{2f}^{KL} F_0^{K \to \pi} (q^2 = m_a^2)$ ;  $F_0^{K \to \pi} (0) = (1_{\text{LO}} - 0.023_{\text{NLO}})$ 









Matthias Neubert **La Thuile 2024: Axion-Like Particles @ Colliders** [Cornella, Galda, MN 2023] *<sup>L</sup>*ˆ8*,r*(*µ*)=0*.*<sup>63</sup> *<sup>±</sup>* <sup>0</sup>*.*25, all at the scale *<sup>µ</sup>* <sup>=</sup> *<sup>m</sup>*⇢. From (2.52), it follows that *F*⇡ = 2024: Axion-Like Particles @ Colliders *F F F F F P ZO23* + 2*m*<sup>2</sup> Figure 3.4, when the initial-state kaon in graph *L*<sup>8</sup> decays into two pions, or when the final-state  $\sim$  two-pion state  $\sim$  two-pion state (remaining graphs). However, the state (remainin  $\blacksquare$  La Thuile 2024: Axion-Like Particles @ Colliders Figure 3.4: Feynman diagrams contributing the *K* ! ⇡*a* at NLO generated by e.g., we obtain *<sup>L</sup>*ˆ4*,r*(*µ*)=0*.*<sup>00</sup> *<sup>±</sup>* <sup>0</sup>*.*38, *<sup>L</sup>*ˆ5*,r*(*µ*)=1*.*<sup>52</sup> *<sup>±</sup>* <sup>0</sup>*.*13, *<sup>L</sup>*ˆ<sup>7</sup> <sup>=</sup> 0*.*<sup>38</sup> *<sup>±</sup>* <sup>0</sup>*.*25, and proportional to *G*<sup>8</sup> in the limit where h*aµ*i = 0 and ✓ = 0 (i.e. h*c<sup>a</sup>*i = 0 and *cGG* = 0). *i*, Thuile 2024: Axion-Like Particles @ Colliders  $\bullet$ 

### Contributions proportional to *G*8 (for *m<sup>a</sup>* = 0):

• Modest NLO corrections with sizable uncertainties

Matthias Neubert **La Thuile 2024: Axion-Like Particles @ Colliders** 

## ALP production in rare kaon decays

![](_page_24_Picture_8.jpeg)

$$
i\mathcal{A}_{\text{LO}}^{G_8} = \frac{G_8 F_\pi^2 m_K^2}{2f} \left[ 1.88 \tilde{c}_{GG} - 0.02 c_{uu}^a - 0.48 (c_{dd}^a + c_{ss}^a) \right]
$$

$$
i\mathcal{A}_{\text{NLO}}^{G_8} = \frac{G_8 F_\pi^2 m_K^2}{2f} \left[ (-0.25 \pm 0.43 \pm 0.61) \tilde{c}_{GG} + (5.21 \pm 1.7) \right]
$$

 $(-0.25 \pm 0.43 \pm 0.61)$   $\tilde{c}_{GG} + (5.21 \pm 1.03 \pm 6.52) \cdot 10^{-3}$   $c_{uu}^a$  $+$  (0.06  $\pm$  0.11  $\pm$  0.16) ( $c_{dd}^a + c_{ss}^a$ )  $\overline{1}$ 

### Contributions proportional to G<sub>8</sub>:

15

![](_page_25_Figure_2.jpeg)

• Weak dependence on ALP mass, except for  $m_a \approx m_{\pi^0}$ 

![](_page_25_Picture_7.jpeg)

- Only a single physical ALP coupling enters, but the low-energy coupling  $G_8^\theta$  is unknown 8
- Modest NLO corrections with sizable uncertainties

 $\tilde{c}_{GG}$ 

## ALP production in rare kaon decays

### Contribution proportional to G<sub>8</sub>θ:

![](_page_26_Picture_10.jpeg)

![](_page_26_Figure_8.jpeg)

$$
i \mathcal{A}_{\text{LO+NLO}}^{G_8^{\theta}} = \frac{G_8^{\theta} F_{\pi}^2 m_K^2}{2f}
$$
  
 
$$
\times \left[ -1.84_{\text{LO}} + (0.25 \pm 0.43 \pm 0.60)_{\text{NLO}} \right]
$$

### Interesting search channel  $K^ \rightarrow \pi^- a$

## Bounds on ALP couplings

- NA62 experimental limits on *K*<sup>−</sup> → *π*−*X* imply bounds on ALP couplings (one at a time), which we express in the form of parameters  $\Lambda_{c_i}^{\mathrm{eff}}$  $c_i^{\text{eff}} = f / |c_i|$ [NA62:[2103.15389]
- New-physics scales probed range from few to tens of TeV

$$
^{(*)} \quad \text{assuming } G_8^{\theta} = 0
$$

Matthias Neubert La Thuile 2024: Axion-Like Particles @ Colliders couplings *c<sup>i</sup>* at the scale *µ* for the cases *m<sup>a</sup>* = 0 and *m<sup>a</sup>* = 200 MeV, derived

![](_page_27_Picture_9.jpeg)

![](_page_27_Picture_306.jpeg)

*ca*

*dd c<sup>a</sup>*

*ss*

(⇤⇤) 8 4 (⇤⇤) 23 22 [Cornella, Galda, MN 2023]

### Interesting search channel  $K^ \rightarrow \pi^- a$

## Bounds on ALP couplings

- NA62 experimental limits on *K*<sup>−</sup> → *π*−*X* imply bounds on ALP couplings (one at a time), which we express in the form of parameters  $\Lambda_{c_i}^{\mathrm{eff}}$  $c_i^{\text{eff}} = f / |c_i|$ [NA62:[2103.15389]
- New-physics scales probed range from few to tens of TeV
- Very strong bounds on flavor-changing ALP couplings call for a flavor symmetry, else:

 $^{10}\,{\rm GeV}$  and the e $^{10}\,{\rm GeV}$  $f_a \sim f > 30 \cdot 10^{10} \text{ GeV}$ 

Matthias Neubert La Thuile 2024: Axion-Like Particles @ Colliders couplings *c<sup>i</sup>* at the scale *µ* for the cases *m<sup>a</sup>* = 0 and *m<sup>a</sup>* = 200 MeV, derived

![](_page_28_Picture_10.jpeg)

![](_page_28_Picture_328.jpeg)

्<br>सन्दर्भ सामग्रीहरू सामग्रीहरू सामग्रीहरू सामग्रीहरू सामग्रीहरू सामग्रीहरू सामग्रीहरू सामग्रीहरू सामग्रीहरू साम

*ca*

*dd c<sup>a</sup>*

*ss*

### Interesting search channel  $K^ \rightarrow \pi^- a$

## Bounds on ALP couplings

- NA62 experimental limits on *K*<sup>−</sup> → *π*−*X* imply bounds on ALP couplings (one at a time), which we express in the form of parameters  $\Lambda_{c_i}^{\mathrm{eff}}$  $c_i^{\text{eff}} = f / |c_i|$ [NA62:[2103.15389]
- New-physics scales probed range from few to tens of TeV
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 $\sqrt{f_a} \sim f > 30 \cdot 10^{10} \, \mathrm{GeV}^2$ 

Matthias Neubert La Thuile 2024: Axion-Like Particles @ Colliders couplings *c<sup>i</sup>* at the scale *µ* for the cases *m<sup>a</sup>* = 0 and *m<sup>a</sup>* = 200 MeV, derived

![](_page_29_Picture_12.jpeg)

![](_page_29_Picture_376.jpeg)

*ca*

*dd c<sup>a</sup>*

*ss*

(⇤⇤) 8 4

*ss*

UUSINOIOGICAI Upper DOUNA:  $\rm \frac{10}{\rm \, GeV}$   $\rm \frac{2 \cdot 10^9 \rm \, GeV}$  (DFSZ) Cosmological upper bound:  $f_a \lesssim 10^{10} \, \text{GeV} \quad \text{(KSVZ)}$ 

[Gorghetto, Hardy, Villadoro 2021]

- Large flavor-changing ALP couplings can be avoided by assuming a **figure v-universal**  $\begin{array}{ccc} a & a & a \ a & a & b \end{array}$  $ALP$  at the UV scale  $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects ated by RG effects and the ALP–fermion contributions to the ALP–fermion contribution couplings. In the second diagram contribution contribution contributions of the second diagram contribution couplings. In the second diag

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## Bounds on ALP couplings *a* P COUNDANCS

[Cornella, Galda, MN 2023]

### $10-5$  T<sup>x</sup> T<sup>t</sup>  $\alpha$   $\alpha$   $\beta$   $\alpha$  (*p*)  $\alpha$   $\alpha$   $\alpha$  (*p*)  $\alpha$   $\alpha$   $\alpha$  (*p*)  $\alpha$   $\alpha$   $\alpha$  (*p*)  $\alpha$  $G = \mathbf{10}$   $V_{td}V_{ts}$  [1.9  $\cdot$  10  $C_u(\Lambda) = 0.1 C_G(\Lambda) = 2.8C$  WW  $[k_d(\mu_X) + k_D(\mu_X)]_{12}^{\text{univ}} \simeq 10^{-5} V_{td}^* V_{ts}$   $[1.9 \cdot 10^3 \tilde{c}_u(\Lambda) - 6.1 \tilde{c}_{GG}(\Lambda) - 2.8 \tilde{c}_{WW}(\Lambda) - 0.02 \tilde{c}_{BB}(\Lambda)]$

![](_page_30_Picture_11.jpeg)

 $\begin{array}{ccc} a & & \\ \hline \cdots & \cdots & \end{array}$ *t t W*

![](_page_30_Figure_7.jpeg)

## Bounds on ALP couplings

- Large flavor-changing ALP couplings can be avoided by assuming a flavor-universal  $ALP$  at the UV scale  $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects

$$
^{(*)} \quad \text{assuming } G_8^{\theta} = 0
$$

 $\blacksquare$ Matthias Neubert = 2000 Methods are derived by setting and the fact of the fact of

![](_page_31_Picture_11.jpeg)

![](_page_31_Picture_318.jpeg)

![](_page_31_Picture_10.jpeg)

$$
f = 1 \,\mathrm{TeV}
$$

cornella, Galda, MN 2023<sub>1</sub> at the flavor in the flavor universal limit for the cases  $\mu$ 

## Bounds on ALP couplings

- Large flavor-changing ALP couplings can be avoided by assuming a flavor-universal  $ALP$  at the UV scale  $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects
- Obtained strong bounds on the ALP couplings to gluons, *W*-bosons and quarks are the best particle-physics bounds in the mass range below 340 MeV

 $\blacksquare$ Matthias Neubert = 2000 Methods are derived by setting and the fact of the fact of

![](_page_32_Picture_8.jpeg)

*ci*

![](_page_32_Figure_6.jpeg)

cornella, Galda, MN 2023<sub>1</sub> at the flavor in the flavor universal limit for the cases  $\mu$ 

### Bounds on ALP couplings  $F(\cdot)$ couplings and the scale and the scale as a flavor universal ALP as a function of the scale  $\mathbb{R}^n$  as a function of the scale  $\mathbb{R}^n$

<sup>20</sup> [Cornella, Galda, MN 2023]

![](_page_33_Picture_9.jpeg)

Logarithmic dependence of the effective new-physics scales on *f*:

![](_page_33_Figure_6.jpeg)

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![](_page_33_Figure_2.jpeg)

## Figure 4.4: 90% CL in the election of the elec

### Dependence of  $\Lambda_{\tilde{c},cc}^{\rm eff}$  on the low-energy constant  $G_8^{\theta}$ :  $\tilde{c}_{GG}$ 8  $\mathbf{f} = \mathbf{f} \cdot \mathbf{f}$  $m_{\tilde{c}_{GG}}$  bependence of  $\Lambda_{\tilde{c}_{GG}}$  on the low-energy  $\Omega$  $G_8^\theta$  $\frac{\theta}{8} = -\frac{G_F}{\sqrt{2}}$  $V_{ud}^*V_{us}g_8^\theta$

### Other flavor bounds (exa $|$ nples)  $\bm{B}_s \rightarrow \mu^+\mu^+$  $B \to K^* \bar{\nu} \nu$ *K*  $\rightarrow$  1  $\sum_{i=1}^{n}$

### ALP—*uR* coupling in the UV:

*B* $\uparrow$ *K* $\vdash$ + $\vdash$ 

### ALP-*d<sub>R</sub>* coupling in the UV:

 $K^+ \to \pi^+ \bar{\nu} \nu$ 

. The interest of the interest

![](_page_34_Picture_8.jpeg)

*KL* $\uparrow$ ⇡ $\circ$ *µ*+*µKL* $\uparrow$ ⇡ $\circ$ *e* $\, + \,$ *e*

![](_page_34_Figure_2.jpeg)

## Conclusions

• Axions and axion-like particles belong to a class of well-motivated light BSM particles

• They are interesting targets for searches in high-energy physics, using collider, flavor,

- with weak couplings to the Standard Model
- and precision probes
- Examples from Higgs physics ( $h \to aa \to 4\gamma$ ) and rare meson decays ( $K^-\to\pi^+a$ ) physics bounds (for *m<sup>a</sup>* < 340 MeV) on almost all ALP couplings to the SM

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have been discussed in detail, with the latter process providing the strongest particle-

![](_page_35_Picture_11.jpeg)

Th*ank you!*