Portal effective theories

[2105.06477]

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Searching for long-lived particles at the LHC and beyond
Tenth workshop of the LLP Community

Axion-like particles (ALPs)

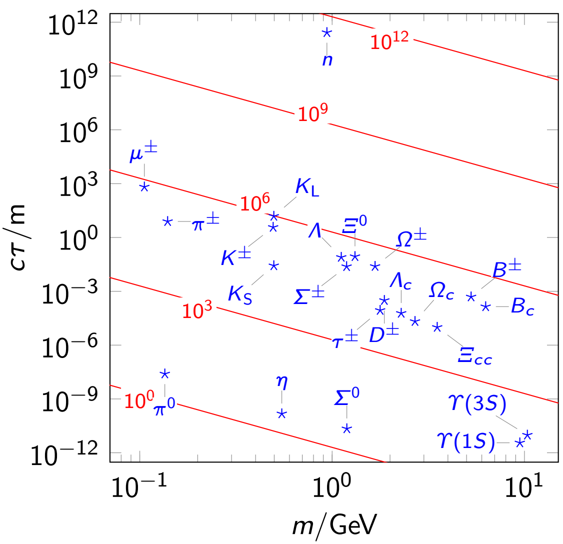
ALP mass and gauge interaction terms

$$\mathcal{L} \supset \frac{1}{2} m_a^2 a^2 + \frac{\alpha_s}{8\pi} \frac{a}{f_a} \widetilde{G} G + \frac{\alpha_{EM}}{8\pi} \frac{a}{f_a} \widetilde{F} F$$

Partial widths

$$\Gamma_g = \frac{\alpha_s^2}{32\pi^3} \frac{m_a^3}{f_a^2}, \qquad \Gamma_\gamma = \frac{\alpha_{EM}^2}{32\pi^3} \frac{m_a^3}{f_a^2}$$

ALPs lifetime



SM particles and ALP decay constant f_a/GeV

Effective theories of the Standard Model

Effective field theories (EFTs)

- include all fields of interest
- consist of all operators allowed by symmetry of the theory
- non-renormaliseable operators encode heavy (new) physics

SM and heavy NP

EFT fields and symmetries

SMEFT, HEFT, LEFT,
NRQCD, HQET, χPT, ...

$\downarrow$

SM operators

O_n^{SM}

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SMEFT

- consists of all SM fields
- operators compatible with SM gauge group
- used to constrain NP models
- see also Higgs EFT

LEFT

- heavy SM fields are integrated out
- generalises Fermi's four fermion theory
- SM (with extensions) at low energies

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- heavy SM fields are integrated out
- generalises Fermi's four fermion theory
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χPT

- exploits light quark flavour symmetry
- light meson interactions

HQET

- exploits mass hierarchy within meson
- interactions of mesons with one heavy quark

(p)NRQCD

- interactions of mesons with two heavy quarks
- treats heavy mesons non-relativistically

Portal effective field theories

Hidden sector

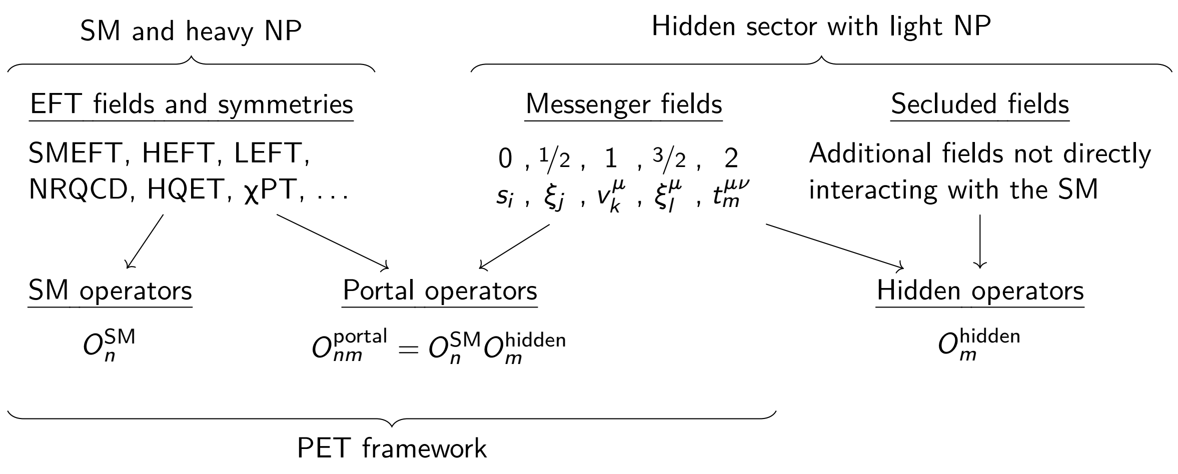
- contains messenger fields
- can entail a complicated secluded sector

Messenger fields

- interact feebly with the SM
- forms with the SM fields the portal operators

Secluded sector

- fields which are not directly coupled to SM
- additional interactions of the messengers
- mass generation mechanism for messenger



Portal currents

SM operators

$$O_n^{\mathrm{SM}} = O_n^{\mathrm{SM}}(q, \ell, \gamma, g, \dots)$$

Hidden operators

$$O_m^{\mathrm{hidden}} = O_m^{\mathrm{hidden}}(s_i, \xi_j, v_k^\mu, \dots)$$

Form portal operators

$$O_{nm}^{\mathrm{portal}} = O_n^{\mathrm{SM}} O_m^{\mathrm{hidden}}$$

Can be collected in Portal currents

$$J_n^{\mathrm{portal}} = \sum_m O_{nm}^{\mathrm{portal}}$$

Capturing the portal interactions of the SM

$$\mathcal{L}^{\mathrm{portal}} = \sum_n J_n^{\mathrm{portal}} O_n^{\mathrm{SM}}$$

For example: The axial anomaly

$$\mathcal{L}_Q^\theta = -\theta \frac{\mathrm{tr}_c \widetilde{G}_{\mu\nu} G^{\mu\nu}}{(4\pi)^2}$$

$G_{\mu\nu}$ Gluon field strength
θ QCD vacuum angle

In terms of current θ and operator w

$$\mathcal{L}_Q^\theta = -\theta w \qquad w = \frac{\mathrm{tr}_c \widetilde{G}_{\mu\nu} G^{\mu\nu}}{(4\pi)^2}$$

Scalar axial current S_θ contains NP

$$\theta \to \Theta = \theta + S_\theta$$

E.g. Axion like particle a

$$S_\theta = c_\theta \frac{a}{f_a}$$

More complicated models

$$S_\theta = c_\theta \frac{a}{f_a} + \dots$$

Portal SMEFT operators

Renormaliseable operators

	d	Higgs	Yukawa + h.c.	Fermions
s_i	3	$s_i \lvert H \rvert^2$		
	4	$s_i s_j \lvert H \rvert^2$		
ξ_a + h.c.	4		$\xi_a \ell_b \widetilde{H}^\dagger$	
v^μ	4	$v_\mu v^\mu \lvert H \rvert^2$ $\partial_\mu v^\mu \lvert H \rvert^2$ $v^\mu H^\dagger \overleftrightarrow{D}_\mu H$		$v^\mu q_a^\dagger \bar{\sigma}_\mu q_b$ $v^\mu \bar{u}_a^\dagger \sigma_\mu \bar{u}_b$ $v^\mu \bar{d}_a^\dagger \sigma_\mu \bar{d}_b$ $v^\mu \ell_a^\dagger \bar{\sigma}_\mu \ell_b$ $v^\mu \bar{e}_a^\dagger \sigma_\mu \bar{e}_b$

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Non-renormaliseable operators of dimension 5

	Higgs	Yukawa + h.c.	Gauge bosons
s_i	$s_i s_j s_k \lvert H\rvert^2$ $s_i D^\mu H^\dagger D_\mu H$ $s_i \lvert H\rvert^4$	$s_i q_a \overline{u}_b \widetilde{H}^\dagger$ $s_i q_a \overline{d}_b H^\dagger$ $s_i \ell_a \overline{e}_b H^\dagger$	$s_i G_{\mu\nu}^a G_a^{\mu\nu}$ $s_i W_{\mu\nu}^a W_a^{\mu\nu}$ $s_i B_{\mu\nu} B^{\mu\nu}$ $s_i G_{\mu\nu}^a \widetilde{G}_a^{\mu\nu}$ $s_i W_{\mu\nu}^a \widetilde{W}_a^{\mu\nu}$ $s_i B_{\mu\nu} \widetilde{B}^{\mu\nu}$
ξ_a + h.c.	$\xi_a \xi_b \lvert H\rvert^2$	$\xi_a^\dagger \overline{\sigma}^\mu \ell_b D_\mu \widetilde{H}^\dagger$	$\xi_a \sigma^{\mu\nu} \xi_b B_{\mu\nu}$

Portal SMEFT currents

Portal Lagrangian

$$\mathcal{L}_{\text{portal}} = \mathcal{L}_{\text{EW}}^{H} + \mathcal{L}_{\text{EW}}^{Y} + \mathcal{L}_{\text{EW}}^{F} + \mathcal{L}_{\text{EW}}^{V}$$

Individual parts

$$\mathcal{L}_{\text{EW}}^{H} = S_m^H |H|^2 + \frac{1}{2} S_\lambda^H |H|^4 + S_\kappa^H D^\mu H^\dagger D_\mu H + \mathrm{i}\, V_H^\mu \; H^\dagger \overleftrightarrow{D}_\mu H \;,$$

$$\mathcal{L}_{\text{EW}}^{Y} = \boldsymbol{S}_m^e \ell \overline{e} H^\dagger + \boldsymbol{S}_m^d q \overline{d} H^\dagger + \boldsymbol{S}_m^u q \overline{u} \widetilde{H}^\dagger + \Xi \ell \widetilde{H}^\dagger + \Xi_\mu \ell D^\mu \widetilde{H}^\dagger + \text{h.c.}\,,$$

$$\mathcal{L}_{\text{EW}}^{F} = \boldsymbol{V}_q^\mu q^\dagger \overline{\sigma}_\mu q + \boldsymbol{V}_\ell^\mu \ell^\dagger \overline{\sigma}_\mu \ell + \boldsymbol{V}_u^\mu \overline{u}^\dagger \sigma_\mu \overline{u} + \boldsymbol{V}_d^\mu \overline{d}^\dagger \sigma_\mu \overline{d} + \boldsymbol{V}_e^\mu \overline{e}^\dagger \sigma_\mu \overline{e}\,,$$

$$\mathcal{L}_{\text{EW}}^{V} = (S_\omega^B B_{\mu\nu} + S_\theta^B \widetilde{B}_{\mu\nu} + T_{\mu\nu}^B) B^{\mu\nu} + (S_\omega^W W_{\mu\nu} + S_\theta^W \widetilde{W}_{\mu\nu}) W^{\mu\nu} + (S_\omega G_{\mu\nu} + S_\theta \widetilde{G}_{\mu\nu}) G^{\mu\nu}$$

Portal SMEFT

- at dimension 5 is encoded in 21 portal currents
- serves as starting point for construction of EFT for lower energies

Portal LEFT currents

After integrating out heavy SM bosons

interactions described by operators of dimension $5 + 2 = 7$

EW QCD operators and portal currents (gluon normalisation $D_\mu = \partial_\mu - \mathrm{i}\, G_\mu$)

SM operator	current	
$w = \operatorname{tr}_c \widetilde{G}_{\mu\nu} G^{\mu\nu} / (4\pi)^2$	$\Theta = \theta + S_\theta$	vacuum angle
$\Upsilon = \operatorname{tr}_c G_{\mu\nu} G^{\mu\nu} / (4\pi)^2$	$\Omega = 2\pi/\alpha + S_\omega$	fine structure constant
$\boldsymbol{Q}_a^{\dot a} = q_a \overline{q}^{\dot a}$	$\boldsymbol{M} = \boldsymbol{m} + \boldsymbol{S}_m$	mass

Portal LEFT current Lagrangian

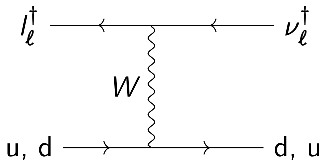
$$\mathcal{L}_Q = \Theta w - \Omega \Upsilon - \operatorname{tr}_f \boldsymbol{M}\boldsymbol{Q}$$

Constant SM currents

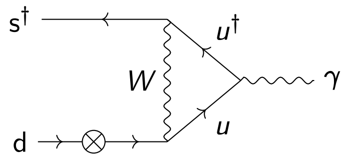
can contain dynamical NP contributions

EW induced portal LEFT currents

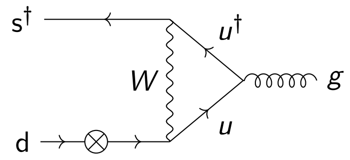
Vector current interactions



Electromagnetic dipole



Chromomagnetic dipole



QCD operators and portal currents

SM operator	current	SM contribution	
$\boldsymbol{Q}^{\mu b}_{a} = q_a \sigma^\mu q^{b\dagger}$	$\boldsymbol{L}^\mu = \boldsymbol{l}^\mu + \boldsymbol{V}_l^\mu$	$\boldsymbol{l}^\mu = e\boldsymbol{q}\mathrm{A}^\mu + \boldsymbol{l}_W^\mu$	left-handed
$\overline{\boldsymbol{Q}}^{\mu \dot b}_{\dot a} = \overline{q}^\dagger_{\dot a} \overline{\sigma}^\mu \overline{q}^{\dot b}$	$\boldsymbol{R}^\mu = \boldsymbol{r}^\mu + \boldsymbol{V}_r^\mu$	$\boldsymbol{r}^\mu = e\boldsymbol{q}\mathrm{A}^\mu$	right-handed
$\boldsymbol{Q}_{\mu\nu}{}_a^{\dot a} = q_a \sigma_{\mu\nu} \overline{q}^{\dot a}$	$\boldsymbol{T}^{\mu\nu} = \boldsymbol{\tau}^{\mu\nu} + \boldsymbol{T}_\tau^{\mu\nu}$	$\boldsymbol{\tau}^{\mu\nu} = \frac{1}{3} F^{\mu\nu} \gamma_A$	tensorial (EM dipole)
$\widetilde{\boldsymbol{Q}}_a^{\dot a} = q_a \sigma_{\mu\nu} G^{\mu\nu} \overline{q}^{\dot a}$	$\boldsymbol{\Gamma} = \gamma + \boldsymbol{S}_\gamma$	$\gamma = \boldsymbol{m}\left(\boldsymbol{\lambda}_\mathrm{s}^\mathrm{d} \sum c_u V_{su}^\dagger V_{ud} + \text{h.c.}\right)$	chromomagnetic

$$\boldsymbol{l}_W^\mu = -v^{-2}\left(V_\mathrm{ud}\boldsymbol{\lambda}_\mathrm{u}^\mathrm{d} + V_\mathrm{us}\boldsymbol{\lambda}_\mathrm{u}^\mathrm{s}\right) \sum l_\ell^\dagger \overline{\sigma}^\mu \nu_\ell + \text{h.c.}\,,$$

Electroweak contributions to the portal LEFT current Lagrangian

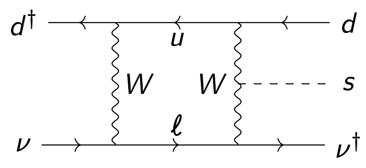
$$\delta\mathcal{L}_Q^\mathrm{EW} = -\operatorname{tr}_f\left(\boldsymbol{L}^\mu \boldsymbol{Q}_\mu + \boldsymbol{R}^\mu \overline{\boldsymbol{Q}}_\mu\right) - \operatorname{tr}_f\left(\boldsymbol{\Gamma}\widetilde{\boldsymbol{Q}} + \boldsymbol{T}^{\mu\nu}\boldsymbol{Q}_{\mu\nu} + \text{h.c.}\right)/(4\pi v)^2$$

4-quark interactions

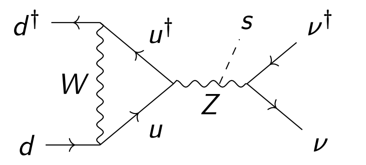
omitted here

Portal LEFT operators

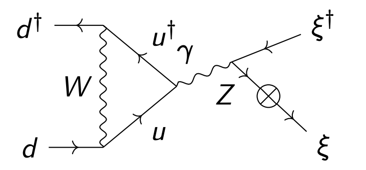
Scalar box diagram



Scalar penguin diagram



Fermionic penguin diagram



Quark flavour conserving operators

	d	Scalar	Vector	Gauge
s_i	4	$s_i\,\overline{\psi}\psi$		
s_i	5	$s_i s_j\,\overline{\psi}\psi$		$s_i\,F_{\mu\nu}F^{\mu\nu}$ $s_i\,F_{\mu\nu}\widetilde{F}^{\mu\nu}$ $s_i\,G_{\mu\nu}G^{\mu\nu}$ $s_i\,G_{\mu\nu}\widetilde{G}^{\mu\nu}$
ξ_a + h.c.	3	$\xi_a\,\nu$		
ξ_a + h.c.	5			$\xi_a\overline{\sigma}_{\mu\nu}\nu\,F^{\mu\nu}$ $\xi_a\overline{\sigma}_{\mu\nu}\xi_b\,F^{\mu\nu}$
v_μ	4		$v_\mu\,\psi^\dagger\overline{\sigma}^\mu\psi$	

Quark flavour violating operators

	d	Two quarks	Quark dipole	Four fermions
s_i	6	$s_i s_j s_k\,\overline{d}d$ $\partial^2 s_i\,\overline{d}d$ $s_i\partial_\mu s_j\,d^\dagger\overline{\sigma}^\mu d$	$s_i\,F^{\mu\nu}\overline{d}\sigma_{\mu\nu}d$ $s_i\,G^{\mu\nu}\overline{d}\sigma_{\mu\nu}d$	
s_i	7	$s_i s_j s_k s_l\,\overline{d}d$		$s_i\;d^\dagger\overline{q}^\dagger\;\;\overline{q}d$ $s_i\;q^\dagger\overline{\sigma}^\mu q\;\;q^\dagger\overline{\sigma}_\mu q$ $s_i\;d^\dagger\overline{\sigma}^\mu d\;\;\overline{q}\sigma_\mu\overline{q}^\dagger$ $s_i\;e^\dagger\overline{\sigma}_\mu\nu\;\;u^\dagger\overline{\sigma}^\mu d$ $s_i\;\nu^\dagger\overline{\sigma}_\mu\nu\;\;d^\dagger\overline{\sigma}^\mu d$
ξ_a h.c.	6	$\xi_a^\dagger\overline{\sigma}_\mu\,e\;d^\dagger\overline{\sigma}^\mu u$ $\xi_a^\dagger\overline{\sigma}_\mu\,\nu\;d^\dagger\overline{\sigma}^\mu d$		

Chiral perturbation theory (χPT)

Matrix valued field of the light mesons

$$\boldsymbol{\Phi} = \begin{pmatrix} \frac{\eta_8}{\sqrt{6}} + \frac{\pi_8}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_8}{\sqrt{6}} - \frac{\pi_8}{\sqrt{2}} & K^0 \\ K^- & \overline{K}^0 & -2\frac{\eta_8}{\sqrt{6}} \end{pmatrix}$$

$$\phi = n_f \frac{\eta_1}{\sqrt{3}}\,, \qquad \boldsymbol{\Phi} = \Phi + \frac{1}{n_f}\phi$$

Flavour symmetry is non-linearly realised

$$\boldsymbol{g}(x) = \exp\frac{\mathrm{i}\,\boldsymbol{\Phi}(x)}{f_0}$$

Energy scale given by meson decay constant

$$f_0 \simeq 63.9\,\mathrm{MeV}\,, \qquad \Lambda_{\chi\mathrm{PT}} = 4\pi f_0$$

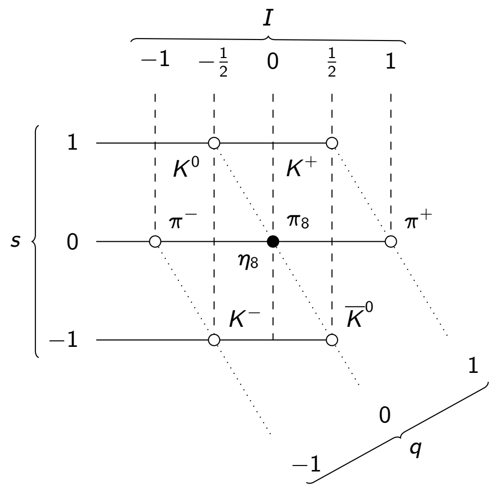
Left-handed Maurer-Cartan field

$$\boldsymbol{u}_\mu = \mathrm{i}\,\boldsymbol{g}\partial_\mu\boldsymbol{g}^\dagger = -\,\mathrm{i}(\partial_\mu\boldsymbol{g})\boldsymbol{g}^\dagger$$

Mass dimensions

$$[\boldsymbol{\Phi}] = 1\,, \qquad [\boldsymbol{g}] = 0\,, \qquad [\boldsymbol{u}_\mu] = 1$$

Quantum numbers of the meson octet



χPT models

SU(2) $\pi^\pm$, π^0

SU(3) $K^\pm$, K^0, $\overline{K}^0$, η_8

U(3) η_1

only U(3) χPT describes η-η' mixing

Lagrangian

Flavour symmetry

$$\boldsymbol{g} \to \boldsymbol{V}\boldsymbol{g}\overline{\boldsymbol{V}}\,, \quad \Phi/f_0 \to \Phi/f_0 - \mathrm{i}\,\mathrm{tr}_f \ln \boldsymbol{V}\overline{\boldsymbol{V}}$$

Covariant derivative

$$D^\mu \boldsymbol{g} = \partial^\mu \boldsymbol{g} - \mathrm{i}(\boldsymbol{L}^\mu \boldsymbol{g} - \boldsymbol{g}\boldsymbol{R}^\mu)$$

Left-handed currents

$$\boldsymbol{U}_\mu = \boldsymbol{u}_\mu - \boldsymbol{L}_\mu + \widehat{\boldsymbol{R}}_\mu\,, \quad \widehat{\boldsymbol{R}}_\mu = \boldsymbol{g}\boldsymbol{R}_\mu\boldsymbol{g}^\dagger\,, \quad \widehat{\boldsymbol{M}} = \boldsymbol{g}\boldsymbol{M}$$

Chirally invariant currents

$$\widehat{M} = \mathrm{tr}_f\,\widehat{\boldsymbol{M}}\,, \quad \widehat{\Theta} = \mathrm{i}(\Theta - \Phi/f_0)$$

Leading order depends on free parameters f_0, b_0, and m_0

$$\mathcal{L} = \frac{f_0^2}{2}\,\mathrm{tr}_f\,\boldsymbol{U}_\mu\boldsymbol{U}^\mu + \left(\frac{f_0^2 b_0}{2}\widehat{M} + \text{h.c.}\right) + \frac{f_0^2 m_0^2}{2n_f}\widehat{\Theta}^2$$

Chromomagnetic dipole contributions

$$\mathcal{L}_U^\Gamma = \frac{\epsilon_{\text{EW}} f_0^2 b_0}{2}\kappa_\Gamma \widehat{\Gamma} + \text{h.c.}\,, \quad \widehat{\Gamma} = \mathrm{tr}_f\,\widehat{\boldsymbol{\Gamma}}\,, \quad \widehat{\boldsymbol{\Gamma}} = \boldsymbol{g}\boldsymbol{\Gamma}$$

Dipole operators

$$\widetilde{\boldsymbol{Q}}_a^{\dot{a}} = q_a \sigma_{\mu\nu} G^{\mu\nu} \overline{q}^{\dot{a}} \qquad \boldsymbol{\Gamma} = \gamma + \boldsymbol{S}_\gamma$$

$$\boldsymbol{Q}_{\mu\nu}{}_a^{\dot{a}} = q_a \sigma_{\mu\nu} \overline{q}^{\dot{a}} \qquad \boldsymbol{T}^{\mu\nu} = \boldsymbol{\tau}^{\mu\nu} + \boldsymbol{T}_\tau^{\mu\nu}$$

Tensor contributions

$$\mathcal{L}_U^{TD^2} = \frac{\epsilon_{\text{EW}}}{4f_0}\kappa_T^{D^2}\,\mathrm{tr}_f\,\widehat{\boldsymbol{T}}_{\mu\nu}\boldsymbol{U}^\mu\boldsymbol{U}^\nu + \text{h.c.}\,, \qquad \mathcal{L}_U^{TV} = \frac{\epsilon_{\text{EW}}}{2f_0}\kappa_T^{LR}\,\mathrm{tr}_f\,\widehat{\boldsymbol{T}}_{\mu\nu}(\boldsymbol{L}^{\mu\nu} + \widehat{\boldsymbol{R}}^{\mu\nu}) + \text{h.c.}$$

Kaon decays

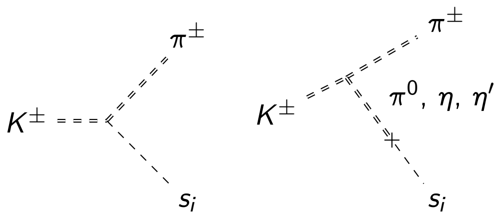
Relevant contributions to $K^\pm \to \pi^\pm s_i$

$$S_\omega = \frac{\epsilon_{\text{UV}}}{v} c_i^{S_\omega} s_i \,, \qquad \boldsymbol{S}_m \supset \epsilon_{\text{UV}} \left(\boldsymbol{c}_i^{S_m} + \boldsymbol{c}_{\partial^2 i}^{S_m} \frac{1}{v^2} \partial^2 \right) s_i \,, \qquad \mathfrak{S}_s = \mathfrak{h}_{si} \frac{\epsilon_{\text{UV}}}{v} s_i \,,$$

$$S_\theta = \frac{\epsilon_{\text{UV}}}{v} c_i^{S_\theta} s_i \,, \qquad \boldsymbol{S}_\gamma = \epsilon_{\text{UV}} \left(\boldsymbol{\lambda}_{\text{d}}^{\text{s}} c_{i\bar{\text{s}}\text{d}}^{\gamma} + \boldsymbol{\lambda}_{\text{s}}^{\text{d}} c_{i\bar{\text{d}}\text{s}}^{\gamma} \right) s_i \,, \qquad \mathfrak{S}_r = \mathfrak{h}_{ri} \frac{\epsilon_{\text{UV}}}{v} s_i \,, \qquad \mathfrak{S}_l = \mathfrak{h}_{li} \frac{\epsilon_{\text{UV}}}{v} s_i$$

Complete transition amplitude

$$\mathcal{A}(K^+ \to \pi^+ s_i) = \mathcal{A}_{\text{direct}} + \mathcal{A}_{\text{mixing}}$$



With complicated functions

$\theta_{\phi^0 s_i}$, $V_{K\pi\phi^0}$, and X_i

Direct production via the trilinear interactions

$$\mathcal{A}_{\text{direct}} = \mathcal{A}_m^{\text{Re}} + \mathcal{A}_h + \mathcal{A}_\omega$$

$$\mathcal{A}_m^{\text{Re}} = -\frac{\epsilon_{\text{UV}} b_0}{2} \left(c_{K\pi s_i} - \operatorname{Re} \boldsymbol{c}_{\partial^2 i\,\text{s}}^{S_m \text{d}} \frac{m_s^2}{v^2} \right) ,$$

$$\mathcal{A}_h = -\frac{\epsilon_{\text{UV}} \epsilon_{\text{EW}}}{2v} X_i \,,$$

$$\mathcal{A}_\omega = \frac{\epsilon_{\text{UV}} \epsilon_{\text{EW}} c_i^{S_\omega}}{\beta_0 v} \left(h_b' m_K^2 - X_0 \right)$$

Indirect production

$$\mathcal{A}_{\text{mixing}} = \mathcal{A}_m^{\text{Im}} + \mathcal{A}_\theta =$$

$$- \mathrm{i}\, \frac{\epsilon_{\text{EW}}}{2 f_0} \left(\theta_{\pi s_i} V_{K\pi\pi} + \theta_{\eta s_i} V_{K\pi\eta} + \theta_{\eta' s_i} V_{K\pi\eta'} \right)$$

ALPs

Lagrangian for ALP a

$$\mathcal{L}_a = \mathcal{L}_a^{\text{hidden}} + \mathcal{L}_a^{\text{portal}}\,, \qquad \mathcal{L}_a^{\text{hidden}} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{2} m_a^2 a^2$$

Portal interactions are with energy scale f_a and Wilson coefficients c_i

$$\mathcal{L}_a^{\text{portal}} = \frac{a}{f_a}\left[c_W W_{\mu\nu}\widetilde{W}^{\mu\nu} + c_B B_{\mu\nu}\widetilde{B}^{\mu\nu} + c_G G_{\mu\nu}\widetilde{G}^{\mu\nu} + \left(\mathrm{i}\, \boldsymbol{c}_u q \overline{u} \widetilde{H}^\dagger + \boldsymbol{c}_d q \overline{d} H^\dagger + \boldsymbol{c}_e \ell \overline{e} H^\dagger + \text{h.c.}\right)\right]$$

Portal currents coupling strong scale QCD to ALPs

$$\boldsymbol{S}_m \supset \boldsymbol{c}_{S_m}\frac{v}{f_a} a\,, \qquad \mathfrak{S}_x = \mathfrak{h}_x \frac{a}{f_a}\,, \qquad S_\theta = c_{S_\theta}\frac{a}{f_a}\,, \qquad \boldsymbol{S}_\gamma = \left(\boldsymbol{\lambda}_{\text{d}}^{\text{s}} c_{\overline{\text{s}}\text{d}}^{\gamma} + \boldsymbol{\lambda}_{\text{s}}^{\text{d}} c_{\overline{\text{d}}\text{s}}^{\gamma}\right)\frac{v}{f_a} a$$

Direct contribution

$$\mathcal{A}_{\text{direct}} = \mathcal{A}_m^{\text{Re}} + \mathcal{A}_h = -\frac{b_0 v}{2 f_a} c_{K\pi a} - \frac{\epsilon_{\text{EW}}}{2 f_a} X_0\,,$$

Indirect contribution

$$\mathcal{A}_{\text{mixing}} = \mathcal{A}_m^{\text{Im}} + \mathcal{A}_\theta = -\,\mathrm{i}\,\frac{\epsilon_{\text{EW}}}{2 f_0}\left(\theta_{\pi a} V_{K\pi\pi} + \theta_{\eta a} V_{K\pi\eta} + \theta_{\eta' a} V_{K\pi\eta'}\right)$$

Light real scalar fields

Lagrangian

$$\mathcal{L}_s = \mathcal{L}_s^{\text{hidden}} + \mathcal{L}_s^{\text{portal}}\,, \qquad \mathcal{L}_s^{\text{hidden}} = \frac{1}{2}\partial_\mu s \partial^\mu s + \lambda s^2 + \lambda' s^3 + \lambda'' s^4$$

Portal interactions with coefficients α_i, c_X, and $\boldsymbol{c}_x$

$$\mathcal{L}_s^{\text{portal}} = \frac{\alpha_0}{\Lambda} s D^\mu H^\dagger D_\mu H + \left(\alpha_1 s + \alpha_2 s^2 + \frac{\alpha_3}{\Lambda} s^3\right) H^\dagger H + \frac{\alpha_4}{\Lambda} s \left(H^\dagger H\right)^2$$
$$+ \frac{s}{\Lambda}\left(\mathrm{i}\, \boldsymbol{c}_u q \overline{u} \widetilde{H}^\dagger + \boldsymbol{c}_d q \overline{d} H^\dagger + \boldsymbol{c}_e \ell \overline{e} H^\dagger + \text{h.c.}\right) + \frac{c_W}{\Lambda} s W_{\mu\nu} W^{\mu\nu} + \frac{c_B}{\Lambda} s B_{\mu\nu} B^{\mu\nu} + \frac{c_G}{\Lambda} s G_{\mu\nu} G^{\mu\nu}$$

Amplitude with parameters κ (equal to 1 if s is the SM Higgs boson with very small mass)

$$\mathcal{A}(K^+ \to \pi^+ h) = \frac{m_K^2}{v}\left[\left(\frac{\kappa_W}{2} - \frac{\kappa_G}{\beta_0}\right)\epsilon_{\text{EW}}(h_8 + (n_f - 1)h_{27})\left(1 + \frac{m_\pi^2 - m_s^2}{m_K^2}\right)\right.$$
$$\left. + \frac{\kappa_{\text{d}} - \kappa_{\text{u}}}{4}\epsilon_{\text{EW}}(h_8 + (n_f - 1)h_{27})\frac{m_\pi^2}{m_K^2} - 2\epsilon_{\text{EW}}\left(\frac{\kappa_W}{2} h_b - \frac{\kappa_G}{\beta_0} h_b'\right) + \kappa_{\text{ds}}\right]$$

Conclusion

Summary

- Light long-lived particles are found in hidden sectors
- EFTs are designed to describe heavy new physics
- We have extended EFTs of the SM to include also portals to hidden sectors
- Portal χPT allows systematic calculation of Kaon decays into hidden messenger particles

Outlook

- D- and B-mesons are captured by HQET and non-relativistic quantum chromodynamics
- Heavy mesons decay into light mesons is captured by soft-collinear effective theory

References

C. Arina, J. Hajer, and P. Klose (2021). ‘Portal Effective Theories: A framework for the model independent description of light hidden sector interactions’. In: *JHEP* 9. DOI: 10.1007/JHEP09(2021)063. arXiv: 2105.06477 [hep-ph]