Portals effective theories

[2105.06477]

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8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics
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FCT Fundação para a Ciência e a Tecnologia

WHERE IS THE NEW PHYSICS HIDING?

Heavy neutral leptons (HNLs)

Right handed neutrinos

$$\mathcal{L}_{\nu_R} = -y_{ai}\bar{\ell}_a\varepsilon\phi\nu_{Ri} - \frac{1}{2}\overline{\nu_{Ri}^c}M_{ij}\nu_{Rj} + \text{h.c.}$$

y_{ai} Yukawa coupling; M_{ij} Majorana mass

Electroweak symmetry breaking

Dirac mass $m_{ai} = v y_{ai}$

Seesaw mechanism

$$m_\nu = -m_{ai}M_{ij}^{-1}m_{bj}^T = -\theta_{ai}M_{ij}\theta_{bj}^T$$

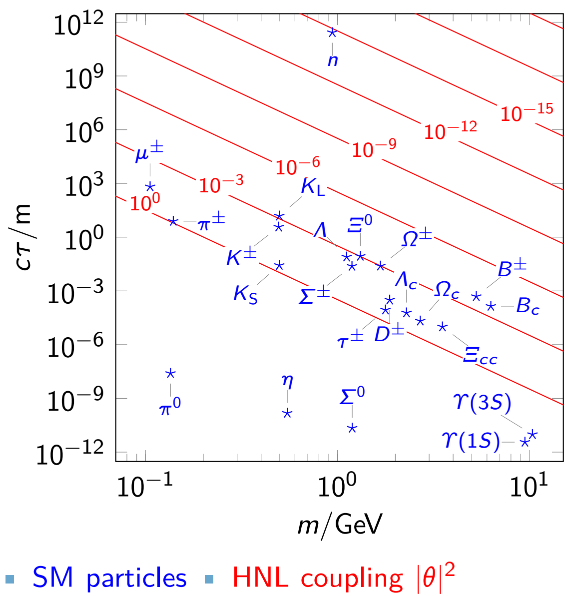
$$\theta_{ai} = m_{aj}M_{ij}^{-1}$$

produces tiny SM neutrino masses

Decay width

$$\Gamma_N \approx \frac{G_F^2}{8\pi^3}|\theta_a|^2 M^5$$

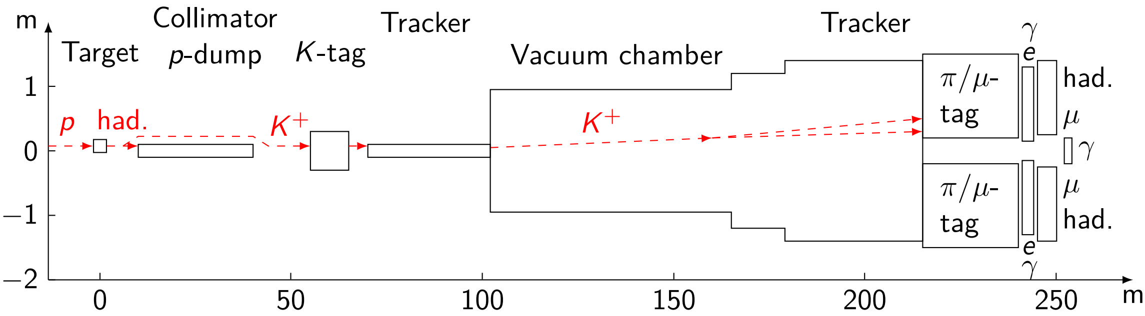
HNL lifetime



NA62

Fixed target experiment in the North Area using the CERN SPS with the goal to

- measure the very rare kaon decay $K^+ \to \pi^+ \nu \overline{\nu}$
- 10 % measurement of the CKM parameter $|V_{td}|$



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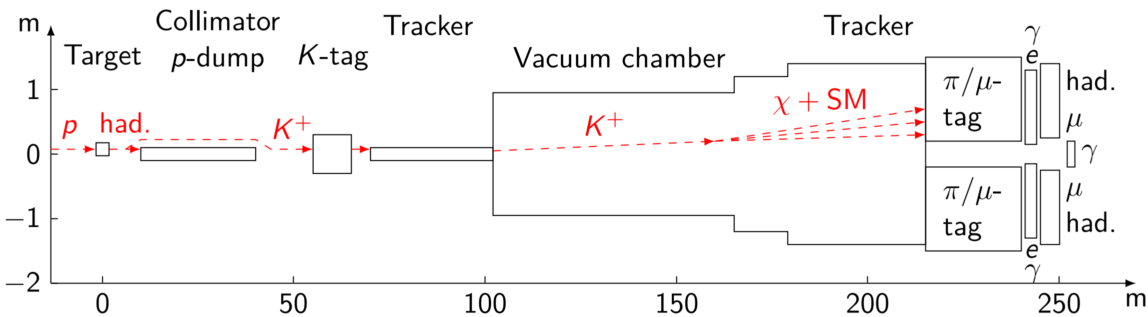

Hidden sectors at NA62

- it can also be used to search for hidden new physics χ such as a heavy neutrino
- Target mode
- only K^+ induced processes

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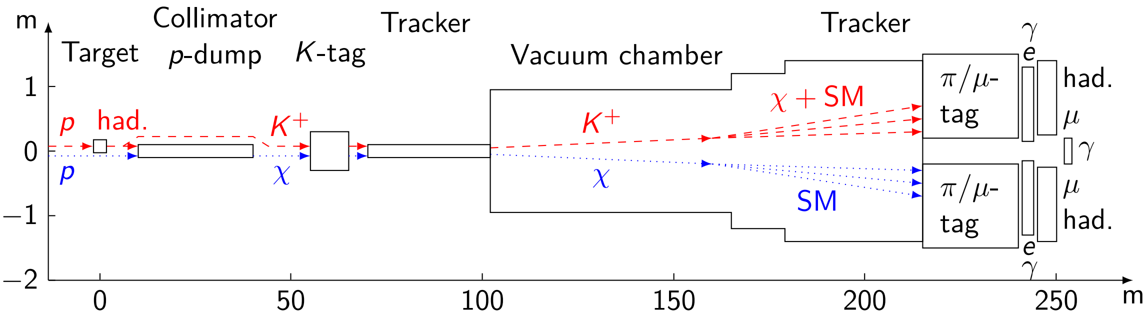
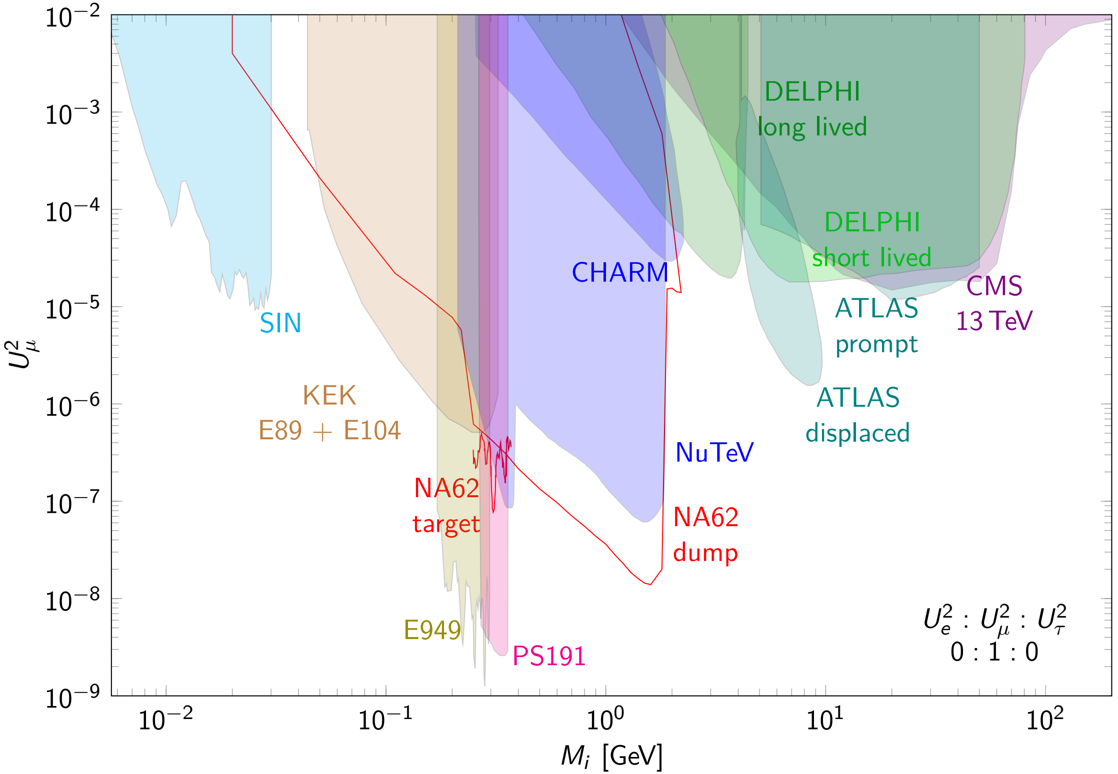


Hidden sectors at NA62

- it can also be used to search for hidden new physics χ such as a heavy neutrino
- Target mode
- only K^+ induced processes
- Dump mode
- D- and B-meson induced processes dominate

pure U_μ^2



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
U_μ^2
DELPHI
long lived
DELPHI
short lived
CHARM
SIN
ATLAS
prompt
CMS
13 TeV
ATLAS
displaced
KEK
E89 + E104
NuTeV
NA62
target
NA62
dump
E949
PS191
$U_e^2 : U_\mu^2 : U_\tau^2$
0 : 1 : 0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
M_i [GeV]

Axion like particles (ALP)

The ALP mass and interaction terms

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

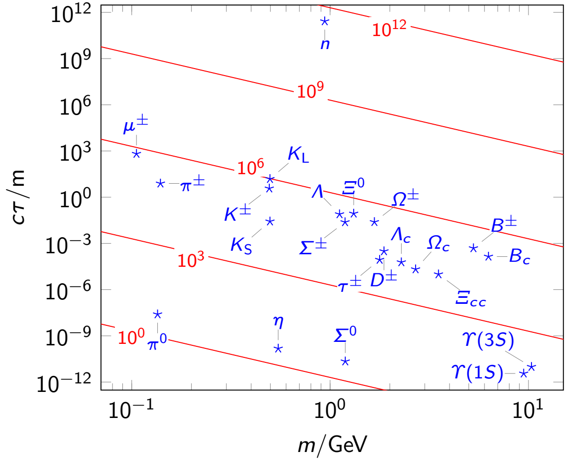
With a model dependent constant c.

Widths

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

With NLO correction factor k.

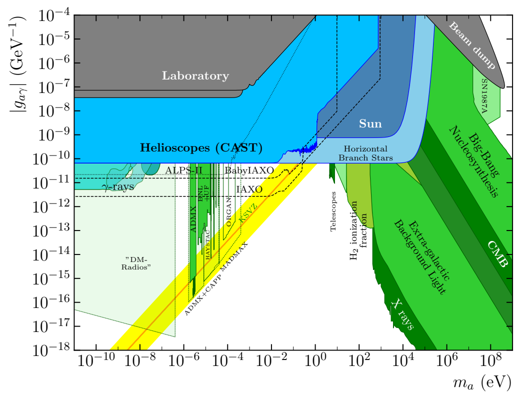
ALPs lifetime



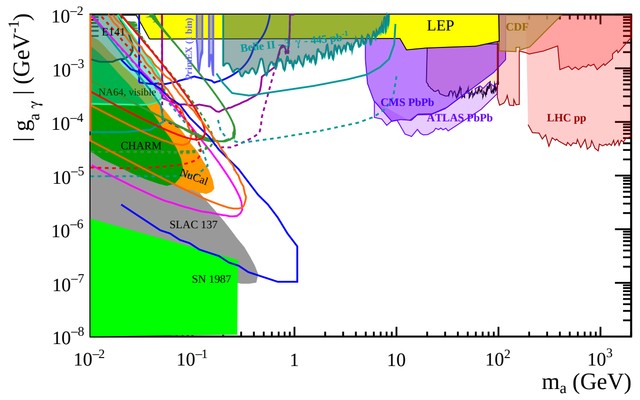
- SM particles
- ALP decay constant f_a/GeV

ALPs exclusion

Low mass



High mass



Effective field theories

Effective theories of the Standard Model

Effective field theories

- 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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SM operators

O_n^{SM}

Standard Model EFT (SMEFT)

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

Light EFT (LEFT)

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

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Chiral perturbation theory (χPT)

- exploits light quark flavour symmetry
- light meson interactions

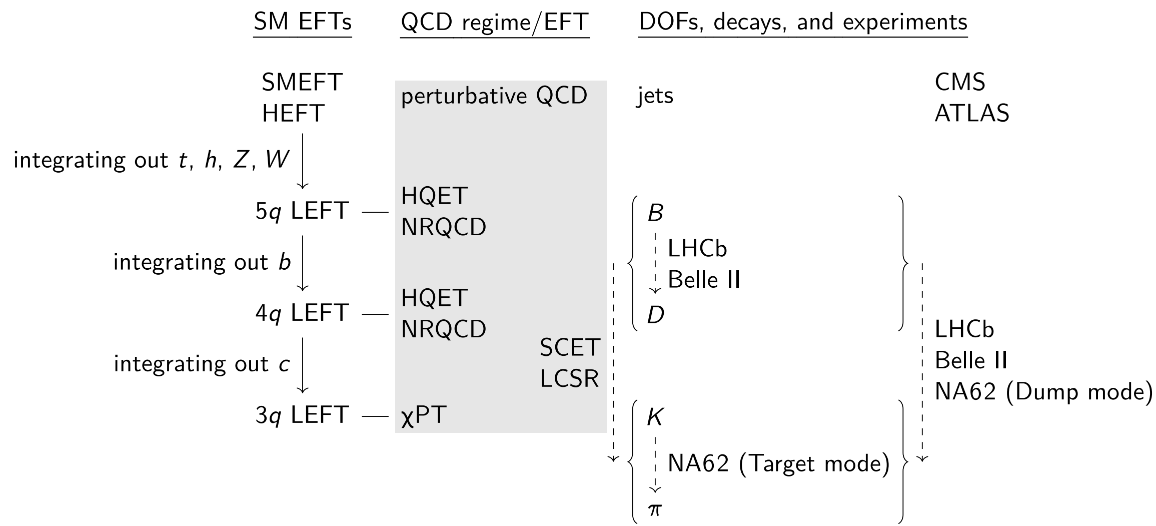
Heavy quark EFT (HQET)

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

non-relativistic QCD (NRQCD)

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

EFTs of the SM and where to use them



Portal effective theories

Portal effective field theories

Hidden sector

- contains mediator fields
- can entail a complicated secluded sector

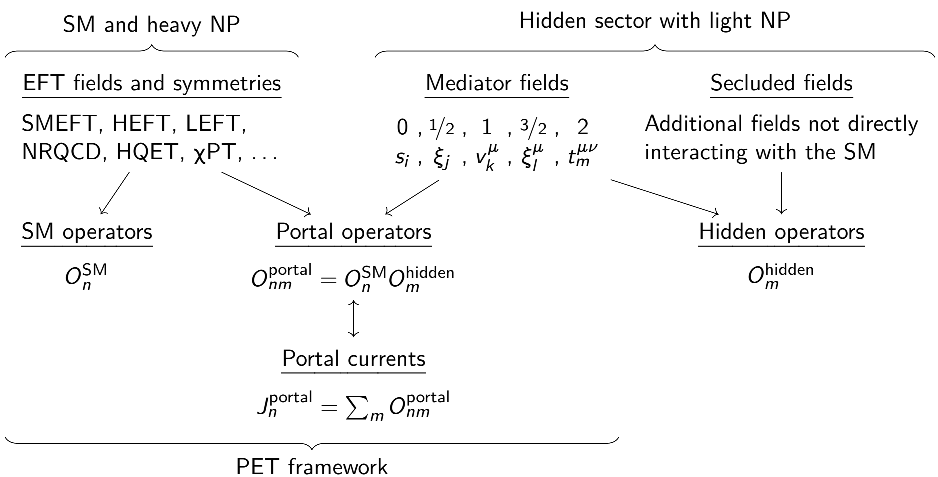
Mediator fields

- 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 mediators
- mass generation mechanism for mediator

Incorporated of necessary portal suppression into EFT power counting



Portal currents

SM operators

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

Hidden operators

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

Form portal operators

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

Can be collected in Portal currents

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

Capturing the portal interactions of the SM

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

For example: The axial anomaly

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

$G_{\mu\nu}$ Gluon field strength

θ QCD vacuum angle

In terms of current θ and operator w

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

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	Gauge bosons
s_i	3	$s_i \vert H\vert^2$			
	4	$s_i s_j \vert H\vert^2$			
ξ_a + h.c.	4		$\xi_a \boldsymbol{\ell}_b \widetilde{H}^\dagger$		
v^μ	4	$v_\mu v^\mu \vert H\vert^2$ $\partial_\mu v^\mu \vert H\vert^2$ $v^\mu H^\dagger \overleftrightarrow{D}_\mu H$		$v^\mu q_a^\dagger \overline{\sigma}_\mu q_b$ $v^\mu \overline{u}_a^\dagger \sigma_\mu \overline{u}_b$ $v^\mu \overline{d}_a^\dagger \sigma_\mu \overline{d}_b$ $v^\mu \boldsymbol{\ell}_a^\dagger \overline{\sigma}_\mu \boldsymbol{\ell}_b$ $v^\mu \overline{e}_a^\dagger \sigma_\mu \overline{e}_b$	

Portal SMEFT operators

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

Non-renormaliseable operators of dimension 5

	d	Higgs	Yukawa + h.c.	Fermions	Gauge bosons
s_i	5	$s_i s_j s_k \lvert H \rvert^2$ $s_i D^\mu H^\dagger D_\mu H$ $s_i \lvert H \rvert^4$	$s_i q_a \overline{u}_b \widetilde{H}^\dagger$ $s_i q_a \overline{d}_b H^\dagger$ $s_i \ell_a \overline{e}_b H^\dagger$		$s_i G^a_{\mu\nu} G_a^{\mu\nu}$ $s_i W^a_{\mu\nu} W_a^{\mu\nu}$ $s_i B_{\mu\nu} B^{\mu\nu}$ $s_i G^a_{\mu\nu} \widetilde{G}_a^{\mu\nu}$ $s_i W^a_{\mu\nu} \widetilde{W}_a^{\mu\nu}$ $s_i B_{\mu\nu} \widetilde{B}^{\mu\nu}$
ξ_a + h.c.	5	$\xi_a \xi_b \lvert H \rvert^2$	$\xi_a^\dagger \overline{\sigma}^\mu \ell_b D_\mu \widetilde{H}^\dagger$		$\xi_a \sigma^{\mu\nu} \xi_b B_{\mu\nu}$

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 the heavy SM bosons

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

QCD operators and portal currents

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

Gluon fields are normalised such that $D_\mu = \partial_\mu - \mathrm{i}\, G_\mu$.

Portal LEFT current Lagrangian

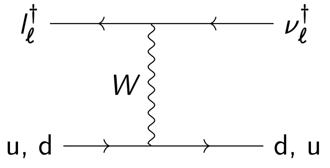
$$\mathcal{L}_Q = \Theta w - \Omega \Upsilon - \langle \boldsymbol{M}\boldsymbol{Q} \rangle_f$$

Constant SM currents

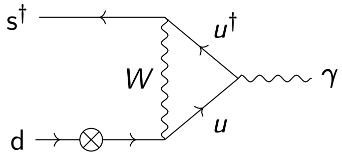
can contain dynamical NP contributions

Electroweak induced portal LEFT currents

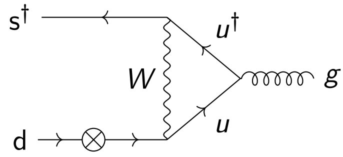
Vector current interactions



Electromagnetic dipole



Chromomagnetic dipole



Electroweak induced portal LEFT currents

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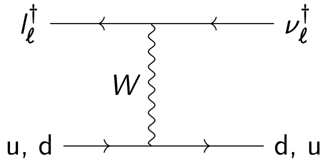

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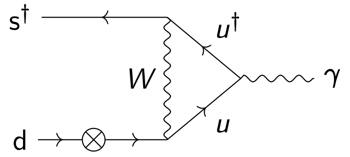

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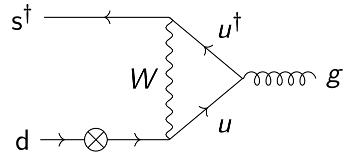

QCD operators and portal currents

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

Electroweak contributions to the portal LEFT current Lagrangian

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

Flavour symmetry in the quark sector

Kinetic Lagrangian is invariant under global flavour rotations

$$q \to \boldsymbol{V} q \,, \qquad \overline{q} \to \overline{q}\overline{\boldsymbol{V}} \,, \qquad (\boldsymbol{V}, \overline{\boldsymbol{V}}) \in G_{LR} = \mathrm{U}(n_f)_L \times \mathrm{U}(n_f)_R$$

Quark bilinear transform as

$$q\overline{q} : \; \boldsymbol{Q} \to \boldsymbol{V}\boldsymbol{Q}\overline{\boldsymbol{V}} \,, \qquad q\sigma_\mu q^\dagger : \; \boldsymbol{Q}_\mu \to \boldsymbol{V}\boldsymbol{Q}_\mu\boldsymbol{V}^\dagger \,, \qquad q\sigma_{\mu\nu}\overline{q} : \; \boldsymbol{Q}_{\mu\nu} \to \boldsymbol{V}\boldsymbol{Q}_{\mu\nu}\overline{\boldsymbol{V}} \,,$$

$$q\sigma_{\mu\nu}G^{\mu\nu}\overline{q} : \; \widetilde{\boldsymbol{Q}} \to \boldsymbol{V}\widetilde{\boldsymbol{Q}}\overline{\boldsymbol{V}} \,, \qquad \overline{q}^\dagger\overline{\sigma}^\mu\overline{q} : \; \overline{\boldsymbol{Q}}_\mu \to \overline{\boldsymbol{V}}^\dagger\overline{\boldsymbol{Q}}_\mu\overline{\boldsymbol{V}} \,.$$

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Currents transform as

$$\boldsymbol{m} \to \overline{\boldsymbol{V}}^\dagger\boldsymbol{m}\boldsymbol{V}^\dagger\,, \qquad \gamma \to \overline{\boldsymbol{V}}^\dagger\gamma\boldsymbol{V}^\dagger\,, \qquad \boldsymbol{\tau}^{\mu\nu} \to \overline{\boldsymbol{V}}^\dagger\boldsymbol{\tau}^{\mu\nu}\boldsymbol{V}^\dagger\,, \qquad \theta \to \theta - \mathrm{i}\langle \ln \boldsymbol{V}\overline{\boldsymbol{V}}\rangle_f\,,$$

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Path integral is invariant under local flavour rotations

$$\boldsymbol{l}^\mu \to \boldsymbol{V}\boldsymbol{l}^\mu\boldsymbol{V}^\dagger + \mathrm{i}\,\boldsymbol{V}\partial^\mu\boldsymbol{V}^\dagger\,, \qquad \boldsymbol{r}^\mu \to \overline{\boldsymbol{V}}^\dagger\boldsymbol{r}^\mu\overline{\boldsymbol{V}} + \mathrm{i}\,\overline{\boldsymbol{V}}^\dagger\partial^\mu\overline{\boldsymbol{V}}$$

Flavour covariant quark derivatives

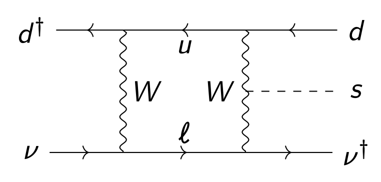
$$\boldsymbol{D}^\mu q = \partial^\mu q - \mathrm{i}\,\boldsymbol{l}^\mu q\,, \qquad \boldsymbol{D}^\mu\overline{q}^\dagger = \partial^\mu\overline{q}^\dagger - \mathrm{i}\,\boldsymbol{r}^\mu\overline{q}^\dagger$$

Field-strength tensors for the left- and right-handed currents

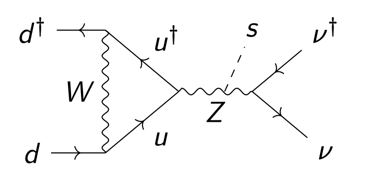
$$\boldsymbol{l}^{\mu\nu} = \partial^\mu\boldsymbol{l}^\nu - \partial^\nu\boldsymbol{l}^\mu - \mathrm{i}[\boldsymbol{l}^\mu,\boldsymbol{l}^\nu]\,, \qquad \boldsymbol{r}^{\mu\nu} = \partial^\mu\boldsymbol{r}^\nu - \partial^\nu\boldsymbol{r}^\mu - \mathrm{i}[\boldsymbol{r}^\mu,\boldsymbol{r}^\nu]$$

Portal LEFT operators

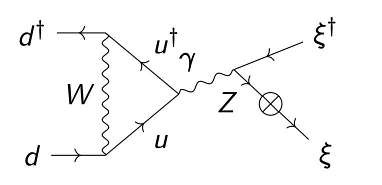
Scalar box diagram



Scalar penguin diagram

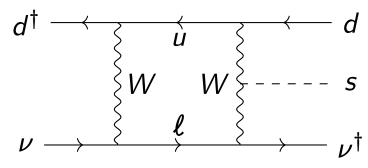


Fermionic penguin diagram

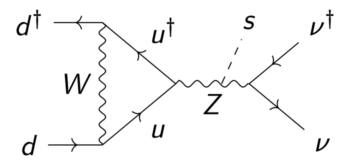


Portal LEFT operators

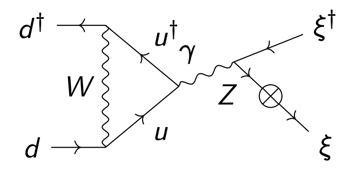
Scalar box diagram



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	$\xi_a^\dagger\overline{\sigma}_\mu\;e\;\;d^\dagger\overline{\sigma}^\mu u$ $\xi_a^\dagger\overline{\sigma}_\mu\;\nu\;\;d^\dagger\overline{\sigma}^\mu d$		

Portal chiral perturbation theory

Chiral perturbation theory

Flavour symmetry is non-linearly realised

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

Matrix valued field of the light mesons

$$\boldsymbol{\Phi} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \pi^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} \end{pmatrix}$$

Energy scale given by meson decay constant

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

Left-handed Maurer-Cartan field

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

Mass dimensions

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

Chiral perturbation theory (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 captures axion interactions

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Matrix valued field of the light mesons

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

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

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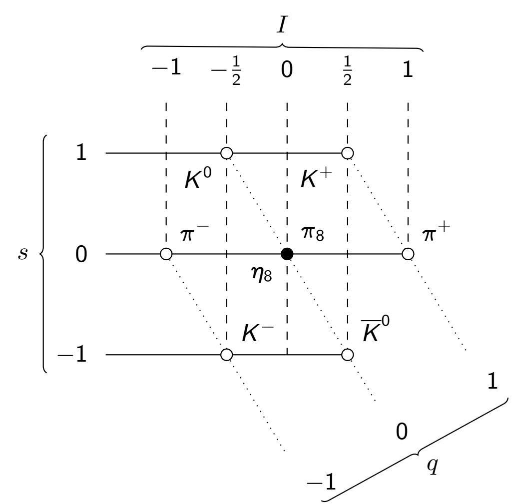
Quantum numbers of the meson octet



Lagrangian

Flavour symmetry

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

Covariant derivative

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

Remember

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

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

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

Lagrangian

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LO depends on free parameters f_0, b_0, and m_0

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

Lagrangian

Flavour symmetry

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

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Remember

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Chirally invariant currents

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

NLO depends on free parameters L_i and Λ_i

$$\begin{aligned}\mathcal{L} = (2L_2 + L_3)\langle \boldsymbol{U}^\mu \boldsymbol{U}_\mu \boldsymbol{U}^\nu \boldsymbol{U}_\nu\rangle_f + L_2\langle \boldsymbol{U}_\mu \boldsymbol{U}_\nu \boldsymbol{U}^\mu \boldsymbol{U}^\nu\rangle_f + \frac{f_0^2}{2n_f}\Lambda_1 U_\mu U^\mu \\ + L_5 b_0\langle \widehat{\boldsymbol{M}}\boldsymbol{U}_\mu \boldsymbol{U}^\mu\rangle_f + \text{h.c.} + L_8 b_0^2\left(\langle \widehat{\boldsymbol{M}^2}\rangle_f + \text{h.c.}\right) + \frac{f_0^2 b_0}{2n_f}\Lambda_2 \widehat{M}\widehat{\Theta} + \text{h.c.} \\ - \mathrm{i}\,L_9\langle \boldsymbol{U}^\mu \boldsymbol{U}^\nu(\boldsymbol{L}_{\mu\nu} + \widehat{\boldsymbol{R}}_{\mu\nu})\rangle_f + L_{10}\langle \boldsymbol{L}^{\mu\nu}\widehat{\boldsymbol{R}}_{\mu\nu}\rangle_f\end{aligned}$$

Field strength tensors of the left- and right-handed currents

$$\boldsymbol{L}^{\mu\nu} = \partial^\mu \boldsymbol{L}^\nu - \partial^\nu \boldsymbol{L}^\mu - \mathrm{i}[\boldsymbol{L}^\mu, \boldsymbol{L}^\nu]\,, \quad \boldsymbol{R}^{\mu\nu} = \partial^\mu \boldsymbol{R}^\nu - \partial^\nu \boldsymbol{R}^\mu - \mathrm{i}[\boldsymbol{R}^\mu, \boldsymbol{R}^\nu]\,, \quad \widehat{\boldsymbol{R}}_{\mu\nu} = \boldsymbol{g}\boldsymbol{R}_{\mu\nu}\boldsymbol{g}^\dagger$$

Low energy realisations (LERs)

Reminder

$$w = \langle \widetilde{G}_{\mu\nu} G^{\mu\nu} \rangle_c / (4\pi)^2 \qquad \boldsymbol{Q} = q\overline{q} \qquad \boldsymbol{Q}^\mu = q\sigma^\mu q^\dagger$$

$$\widetilde{\boldsymbol{Q}} = q\sigma_{\mu\nu} G^{\mu\nu} \overline{q} \qquad \overline{\boldsymbol{Q}}^\mu = \overline{q}^\dagger \overline{\sigma}^\mu \overline{q} \qquad \boldsymbol{Q}_{\mu\nu} = q\sigma_{\mu\nu}\overline{q}$$

LERs associated with the $\boldsymbol{L}_\mu$, $\boldsymbol{R}_\mu$, M, and Θ currents are well established.

$$\boldsymbol{Q}_\mu = -f_0^2 \boldsymbol{U}_\mu \,, \qquad \overline{\boldsymbol{Q}}_\mu = -f_0^2 \boldsymbol{g}^\dagger \boldsymbol{U}_\mu \boldsymbol{g} \,, \qquad \boldsymbol{Q} = -\frac{1}{2} f_0^2 b_0 \boldsymbol{g} \,, \qquad w = -\,\mathrm{i}\, f_0^2 \frac{m_0^2}{n_f} \widehat{\Theta} \,.$$

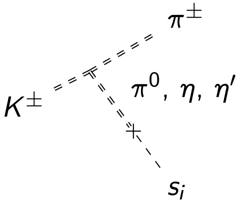
LERs associated with the $\boldsymbol{T}_{\mu\nu}$ and $\boldsymbol{\Gamma}$ currents

$$\boldsymbol{Q}^{\mu\nu} = -f_0 \Big(\kappa_T^{D^2} \boldsymbol{U}^\mu \boldsymbol{U}^\nu + \kappa_T^{LR} (\boldsymbol{L}^{\mu\nu} + \widehat{\boldsymbol{R}}^{\mu\nu}) \Big) \boldsymbol{g} \,, \qquad \widetilde{\boldsymbol{Q}} = -\frac{1}{2} f_0^4 b_0 \kappa_\Gamma \boldsymbol{g}$$

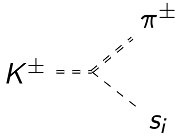
Kaon decay

Kaon decays

Mass mixing



Direct production



Complete transition amplitude

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

Master equation

$$\Gamma(K^+ \to \pi^+ s_i) = 2\pi m_K \left(\frac{\epsilon_{\text{UV}}}{2}\frac{b_0}{4\pi m_K}\right)^2 \rho(x_\pi, x_s)$$
$$\left(\left|\text{Re}\left(c_{K\pi s_i} - \boldsymbol{c}^{S_m \text{d}}_{\partial^2 i\, \text{s}}\frac{m_s^2}{v^2}\right) + \frac{\epsilon_{\text{EW}}}{b_0 v}\left(X_i + 2\frac{c_i^{S_\omega}}{\beta_0}(X_0 - h_b' m_K^2)\right)\right|^2\right.$$
$$\left. + \left|\text{Im}\, c_{K\pi s_i} + \frac{\epsilon_{\text{EW}}}{\epsilon_{\text{UV}} f_0 b_0}(\theta_{\pi s_i} V_{K\pi\pi} + \theta_{\eta s_i} V_{K\pi\eta} + \theta_{\eta' s_i} V_{K\pi\eta'})\right|^2\right) \,.$$

ALPs

The direct contribution is

$$\mathcal{A}_{\text{direct}} = \mathcal{A}_m^{\text{Re}} + \mathcal{A}_h = -\frac{b_0 v}{2f_a} c_{K\pi a} - \frac{\epsilon_{\text{EW}}}{2f_a} X_0\,, \quad X_i = \frac{1}{2}(h_{8i} + (n_f - 1)h_{27i})\left(m_K^2 + m_\pi^2 - m_s^2\right)$$

while the indirect contribution for production via meson-to-axion mixing is

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

where the mixing angles are now

$$\theta_{\pi a} = \frac{f_0}{f_a}\frac{b_0 v c_{a\pi}}{m_a^2 - m_\pi^2}\,, \qquad \theta_{\eta a} = \frac{f_0}{f_a}\frac{b_0 v c_{a\eta} + c_{S_\theta} m_0^2 s_\eta}{m_a^2 - m_\eta^2}\,, \qquad \theta_{\eta' a} = \frac{f_0}{f_a}\frac{b_0 v c_{a\eta'} - c_{S_\theta} m_0^2 c_\eta}{m_a^2 - m_{\eta'}^2}$$

Comparison with literature for direct contribution

- Previous calculations were wrong by 0.16 [2102.13112]
- We reproduce the new result

$$\mathcal{A}(K^- \to \pi^- a) \approx 7.5 \times 10^{-8} \frac{m_K^2}{f_a}$$

Light real scalar fields

Lagrangian

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

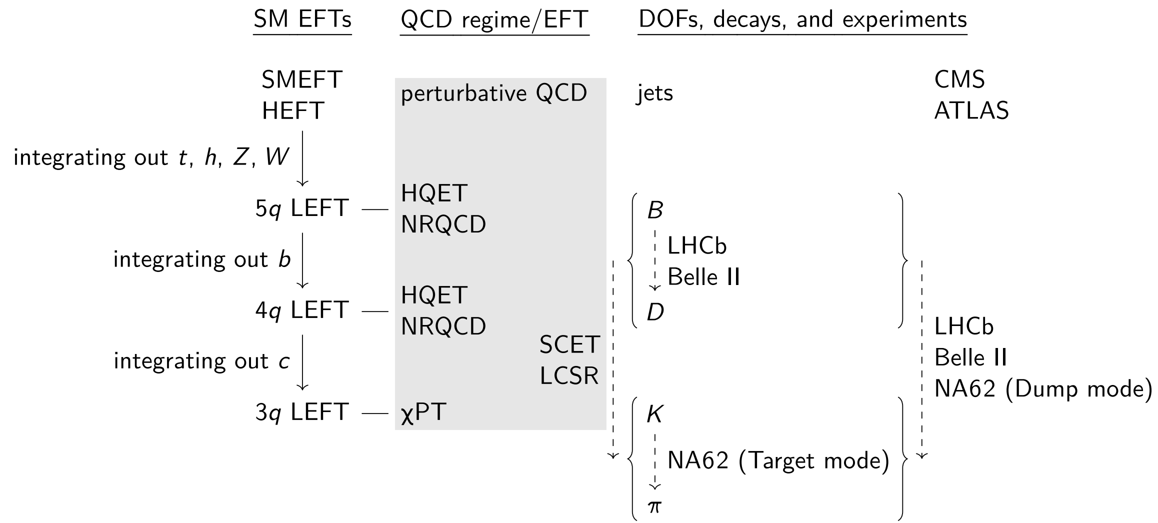
Portal interactions with coefficients α_i, c_X, and $\boldsymbol{c}_x$

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

Amplitude reproduces result from Nucl. Phys. B 343 (1990)

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

Future



- Decay from heavy mesons work in progress
- Constrain currents instead of couplings
- EFT description of portal solution for meson anomalies

Conclusion

- New Physics might be found in hidden sectors
- EFTs are designed to describe heavy New Physics
- Portal EFTs capture new physics interactions involving light mediators
- We have reproduced kaon decays into hidden sectors within χPT
- Other EFTs need to be extended in order to describe the decays of other mesons