Portal Effective Theories

A framework for the model independent description of light hidden sector interactions

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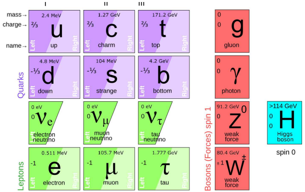
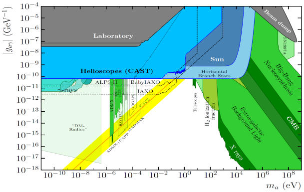
Searching for long-lived particles at the LHC and beyond: Ninth workshop of the LLP Community

arXiv:2105.06477

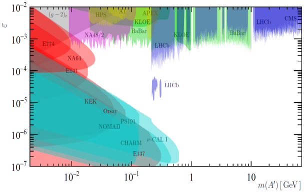
Collaborators: Chiara Arina, Jan Hajer

Model-independent hidden sector searches





arXiv:2102.12143



arXiv:2104.10280

Generic new physics (NP) model below electroweak (EW) scale:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{hidden}} + \mathcal{L}_{\mathrm{portal}}$$

Heavy NP: Model independent description via EFTs (SMEFT, HEFT, etc.)

Light NP: Couple to SM via portals
Intensity Frontier $\Rightarrow$ Meson interactions important

Coupling to generic light hidden sectors?

$\Rightarrow$ Generalize EFT approach

Portal Effective Theory (PET) Framework

SM and heavy NP

EFT fields and symmetries

SMEFT, HEFT, LEFT,
NRQCD, HQET, χPT, …

SM operators

O_n^{SM}

Portal operators

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

Portal currents

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

PET framework

Hidden sector with light NP

Messenger fields

0 , $1/2$, 1 , $3/2$, 2
s_i , ξ_j , v_k^μ , ξ_l^μ , $t_m^{\mu\nu}$

Secluded fields

Additional fields not directly
interacting with the SM

Hidden operators

O_m^{hidden}

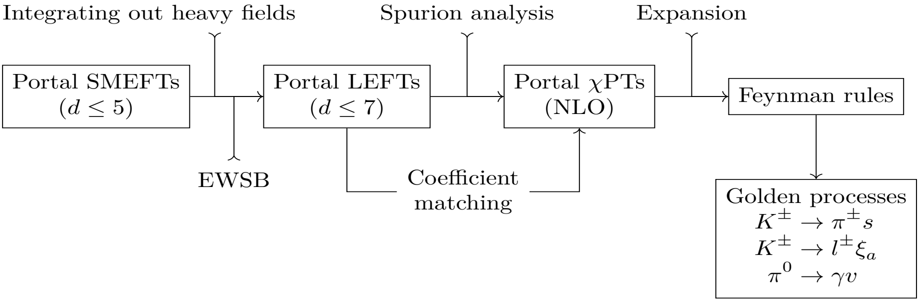
Construct and link multiple PETs

$\Rightarrow$ Translate EW scale $\leftrightarrow$ strong scale $\leftrightarrow$ mesons

Proof of concept: portal SMEFT $\rightarrow$ portal χPT

Physics Focus: (1) Light mesons (E.g. at NA62, MaTHUSLA, KOTO)
(2) Electroweak interactions
(Needed for e.g. $\pi^0 \rightarrow \gamma X$, $K^+ \rightarrow \pi^+ X$)

- We consider single messenger s_i, ξ_i, v^μ (SM gauge singlet; spin 0, 1/2, 1) $\Rightarrow$ **3 sets of PETs**



Strong Scale QCD & χPT Portal Interactions

SM: 4 currents capture quark masses, photons, θ angle:

$$\delta\mathcal{L}_{\text{QCD}} = -q^\dagger\overline{\sigma}_\mu \boldsymbol{l}^\mu q - \overline{q}\sigma_\mu \boldsymbol{r}^\mu \overline{q}^\dagger - \theta\, G_{\mu\nu}\widetilde{G}^{\mu\nu} - \left[\overline{q}\boldsymbol{m}q + \text{h.c.}\right]$$

QCD Flavour symmetry determines meson to current coupling $\Rightarrow$ spurion analysis

Our work: 10 portal currents parametrize new physics:

$$\delta\mathcal{L}_{\text{QCD}} \to -q^\dagger\overline{\sigma}_\mu \boldsymbol{L}^\mu q - \overline{q}\sigma_\mu \boldsymbol{R}^\mu \overline{q}^\dagger - \Omega\, G_{\mu\nu}G^{\mu\nu} - \Theta\, G_{\mu\nu}\widetilde{G}^{\mu\nu}$$
$$-\left[\overline{q}\boldsymbol{M}q + \overline{q}\,\overline{\sigma}^{\mu\nu}\boldsymbol{T}_{\mu\nu}q - \overline{q}\,\boldsymbol{\Gamma}\overline{\sigma}^{\mu\nu}G_{\mu\nu}q + \text{h.c.}\right] + \mathcal{L}_{\overline{q}q\overline{q}q}[H_l, H_r, H_s]$$

Portal χPT: Couple mesons to all portal currents

- We extend spurion appraoch to include new currents
- We estimate resulting new χPT coefficients (Using scale anomaly, QCD condensates, large n_c limit)

Application: Kaon Decays into Hidden Particles

1. Fermionic Messengers: $\mathcal{A}(K^+ \to \ell_a^+ \xi_b)$ depends on **1** portal current
   - Reproduces standard result for HNL
   - Captures models with additional **secluded fields**
2. Scalar Messengers: $\mathcal{A}(K^+ \to \pi^+ s_i)$ depends on **7** portal currents

$$\mathcal{A} = \mathcal{A}_M + \mathcal{A}_{S_\omega} + \mathcal{A}_{S_\theta} + \mathcal{A}_\Gamma + \mathcal{A}_{H_l} + \mathcal{A}_{H_r} + \mathcal{A}_{H_s}$$

   - Captures production of **general spin 0 messengers** (ALPs, light Higgs, complex scalars, sGoldstinos, etc.)
   - Includes i) mixing with mesons, ii) full flavour dependence
   - Encompasses prior model-dependent results for ALPs, light Higgs, etc.

Summary

1. We developed the **PET Framework**
   $\Rightarrow$ couple EFTs to generic light hidden sectors

2. We constructed PETs with single messenger of spin 0, $1/2$, 1 :
   - portal SMEFTs containing all $d \leq 5$ operators
   - portal LEFTs also containing flavour violating $d = 6, 7$ operators
     $\Rightarrow$ **10 portal currents**
   - portal χPT couples mesons to portal currents

3. We computed **generic decay amplitudes**:
   - $\mathcal{A}(K^+ \to \pi^+ s_i)$ (spin 0: e.g. ALP, Higgs portal, *etc.*)
   - $\mathcal{A}(K^+ \to \ell^+ \xi_i)$ (spin $1/2$: e.g. HNL, *etc.*)
   - $\mathcal{A}(\pi^0 \to \gamma v_i)$ (Spin 1 messenger: E.g. Dark photon)

Thank you for your attention!

EW Scale PETs: Portal Operators

	d	Higgs	Yukawa + h.c.	Fermions	Gauge bosons
s_i	3	$s_i\|H\|^2$			
	4	$s_i s_j\|H\|^2$			
	5	$s_i s_j s_k\|H\|^2$ $s_i D^\mu H^\dagger D_\mu H$ $s_i\|H\|^4$	$s_i q_a \overline{u}_b \widetilde{H}^\dagger$ $s_i q_a \overline{d}_b H^\dagger$ $s_i \ell_a \overline{e}_b H^\dagger$		$s_i G^a_{\mu\nu} G^{\mu\nu}_a$ $s_i W^a_{\mu\nu} W^{\mu\nu}_a$ $s_i B_{\mu\nu} B^{\mu\nu}$ $s_i G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a$ $s_i W^a_{\mu\nu} \widetilde{W}^{\mu\nu}_a$ $s_i B_{\mu\nu} \widetilde{B}^{\mu\nu}$
ξ_a + h.c.	4		$\xi_a \ell_b \widetilde{H}^\dagger$		
	5	$\xi_a \xi_b\|H\|^2$	$\xi_a^\dagger \overline{\sigma}^\mu \ell_b D_\mu \widetilde{H}^\dagger$		$\xi_a \sigma^{\mu\nu} \xi_b B_{\mu\nu}$
v^μ	4	$v_\mu v^\mu\|H\|^2$ $\partial_\mu v^\mu\|H\|^2$ $v^\mu H^\dagger \overleftrightarrow{D}_\mu H$		$v^\mu q_a^\dagger \overline{\sigma}_\mu q_b$ $v^\mu \overline{u}_a^\dagger \sigma_\mu \overline{u}_b$ $v^\mu \overline{d}_a^\dagger \sigma_\mu \overline{d}_b$ $v^\mu \ell_a^\dagger \overline{\sigma}_\mu \ell_b$ $v^\mu \overline{e}_a^\dagger \sigma_\mu \overline{e}_b$	

Strong Scale PETs: $d = 6, 7$ and $|\Delta F| = 1$ Portal Operators

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

$K^+ \to \pi^+ s_i$ Interactions

Currents:

$$\Omega \supset \frac{\epsilon_{\text{UV}}}{v} c_i^{S_\omega} s_i \ , \qquad \boldsymbol{M} \supset \epsilon_{\text{UV}} \left(\boldsymbol{c}_i^{S_m} + \boldsymbol{c}_{\partial^2 i}^{S_m} \frac{1}{v^2} \partial^2 \right) s_i \ , \qquad H_x \supset h_{xi} \frac{\epsilon_{\text{UV}}}{v} s_i \ ,$$

$$\Theta \supset \frac{\epsilon_{\text{UV}}}{v} c_i^{S_\theta} s_i \ , \qquad \boldsymbol{\Gamma} \supset \epsilon_{\text{UV}} \left(\boldsymbol{\lambda}_d^s c_{i\bar{s}d}^{\gamma} + \boldsymbol{\lambda}_s^d c_{i\bar{d}s}^{\gamma} \right) s_i$$

Scalar current coupling to Kaons:

$$\mathcal{L}_{\text{portal}} \supset -\frac{b}{2} \epsilon_{\text{UV}} K^+ \pi^- \left(c_{K\pi s_i} + \operatorname{Re} \boldsymbol{c}_{\partial^2 i}^{S_m}{}^{d}_{s} \frac{\partial^2}{v^2} \right) s_i \ ,$$

where

$$c_{K\pi s_i} = \operatorname{Re} \boldsymbol{c}_i^{S_m}{}^{d}_{s} + \frac{\epsilon_{\text{EW}}}{2} \left((m_K^2 - m_\pi^2) \operatorname{Re} \boldsymbol{c}_i^{S_m}{}^{u}_{u} + m_K^2 \operatorname{Re} \boldsymbol{c}_i^{S_m}{}^{d}_{d} - m_\pi^2 \operatorname{Re} \boldsymbol{c}_i^{S_m}{}^{s}_{s} \right) \theta_{K^\pm \pi^\mp}$$
$$- \frac{\epsilon_{\text{EW}}}{2} \left(2 v h_b \left(\frac{m_{ud}}{m_s} \left(\boldsymbol{c}_i^{S_m}{}^{d}_{d} - \boldsymbol{c}_i^{S_m}{}^{s}_{s}{}^{\dagger} \right) + \boldsymbol{c}_i^{S_m}{}^{d}_{d}{}^{\dagger} \right) + \frac{m_{ud} + m_s}{v} h_{bi} - \kappa_\gamma \left(c_{i\bar{d}s}^{\gamma} + c_{i\bar{s}d}^{\gamma\dagger} \right) \right)$$

$\theta_{K^\pm \pi^\mp}$ is kaon to pion mixing angle, m_{ud} is light quark mass

$K^+ \to \pi^+ s_i$ Amplitude

$$\mathcal{A}(K^+ \to \pi^+ s_i) = \mathcal{A}_{\mathrm{Re}\, S_m}(K^+ \to \pi^+ s_i) + \mathcal{A}_{\mathrm{Im}\, S_m}(K^+ \to \pi^+ s_i) + \mathcal{A}_\omega(K^+ \to \pi^+ s_i) + \mathcal{A}_\theta(K^+ \to \pi^+ s_i) + \mathcal{A}_{8+27}(K^+ \to \pi^+ s_i)$$

where

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

$$\mathcal{A}_\omega(K^+ \to \pi^+ s_i) = \frac{\epsilon_{\mathrm{UV}}\epsilon_{\mathrm{EW}} c_i^{S_\omega}}{\beta_0 v}\left(h_b' m_K^2 - \frac{1}{2}\left(h_8 + (3-1)h_{27}\right)\left(m_K^2 + m_\pi^2 - m_s^2\right)\right)$$

$$\mathcal{A}_{8+27}(K^+ \to \pi^+ s_i) = -\frac{\epsilon_{\mathrm{UV}}\epsilon_{\mathrm{EW}}}{4v}\left(h_{8i} + (3-1)h_{27i}\right)\left(m_K^2 + m_\pi^2 - m_s^2\right)$$

$$\mathcal{A}_{\mathrm{Im}\, S_m}(K^+ \to \pi^+ s_i) = -\,\mathrm{i}\,\epsilon_{\mathrm{UV}}\epsilon_{\mathrm{EW}} b\left(c_{s_i\pi}\frac{V_{K\pi\pi}}{m_s^2 - m_\pi^2} + c_{s_i\eta}\frac{V_{K\pi\eta}}{m_s^2 - m_\eta^2} + c_{s_i\eta'}\frac{V_{K\pi\eta'}}{m_s^2 - m_{\eta'}^2}\right)$$

$$\mathcal{A}_\theta(K^+ \to \pi^+ s_i) = \mathrm{i}\,\frac{\epsilon_{\mathrm{UV}}\epsilon_{\mathrm{EW}} c_i^{S_\theta} m_0^2}{v}\left(c_\eta\frac{V_{K\pi\eta'}}{m_s^2 - m_{\eta'}^2} - s_\eta\frac{V_{K\pi\eta}}{m_s^2 - m_\eta^2}\right) .$$

- c_η, s_η are (co-)sine of $\eta - \eta'$ mixing angle, $V_{\phi_a\phi_b\phi_c}$ are SM 3 meson vertices
- $c_{K\pi s_i}$, $c_{s_i\phi_a}$ parametrize coupling to hidden sectors

$K^+ \to \nu_a \xi_b$ Width

Interaction:

$$\mathcal{L}_{\text{portal}} \supset -\epsilon_{\text{UV}} v c^{\nu}_{ba} \ \nu_b \xi_a - \frac{\epsilon_{\text{UV}} f}{v^2} c^{L\dagger}_{\bar{u}s,ba} \ \xi^{\dagger}_a \overline{\sigma}_{\mu} e_b \partial^{\mu} K^+ + \text{h.c.}$$

Width:

$$\Gamma = \left|\theta'_{ba}\right|^2 \Gamma(K^+ \to \ell^+_b \nu_b) \frac{\rho(x_\ell, x_\xi)}{\rho(x_\ell, 0)}, \qquad \theta'_{ba} = \epsilon_{\text{UV}} \left(\frac{c^{\nu}_{ba} v}{m_\xi} + \frac{c^{L}_{\bar{u}s,ba}}{V_{us}} \right)$$

Phasespace factor:

$$\rho(x_\ell, x_\xi) = \left(x_\ell + x_\xi - (x_\ell - x_\xi)^2 \right) \sqrt{\left(\frac{1 - x_\ell - x_\xi}{2} \right)^2 - x_\ell x_\xi} \ , \qquad x_i = \frac{m_i^2}{m_K^2}$$

$\pi^0 \to \gamma v_i$ Width

Interaction:

$$\mathcal{L}_{\text{portal}} \supset \frac{2}{(4\pi)^2 f} \left(2\partial^\mu \boldsymbol{V}^\nu_{v\,u} + \partial^\mu \boldsymbol{V}^\nu_{v\,d}\right) \frac{\pi^0}{\sqrt{2}} e\widetilde{F}_{\mu\nu}, \qquad \boldsymbol{V}^\mu_v = \epsilon_{\text{UV}} \left(\boldsymbol{c}^L_v + \boldsymbol{c}^R_v\right) v^\mu$$

Width:

$$\Gamma(\pi^0 \to \gamma v_i) = 2\epsilon^2_{\text{eff}} \Gamma_{\pi^0 \to \gamma\gamma} \left(1 - \frac{m_v^2}{m_\pi^2}\right)^3, \quad \epsilon_{\text{eff}} = \epsilon_{\text{UV}} \frac{2(\boldsymbol{c}^R_v + \boldsymbol{c}^L_v)_u + (\boldsymbol{c}^R_v + \boldsymbol{c}^L_v)_d}{2e\left(2q_u + q_d\right)}$$