Long-lived particles and portal EFTs

partially based on arXiv:2105.06477

Jan Hajer

Department of Physics, Universität Basel

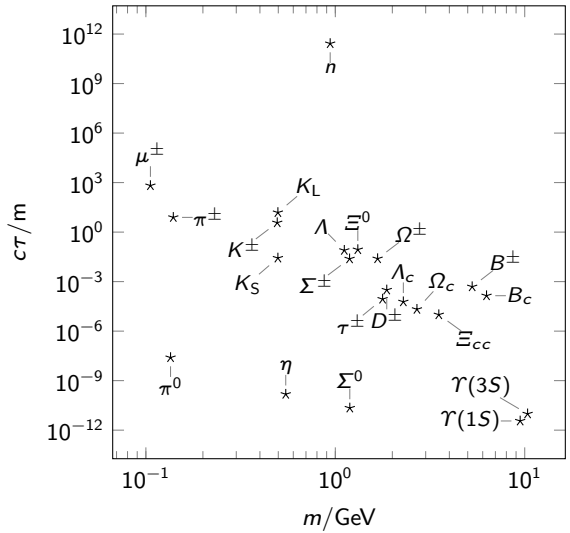
DESY Theory Workshop 2021: Bright Ideas for a Dark Universe

Long-lived particles (LLPs)

LLPs in the SM

- Many particles of the SM are long-lived
- Some are even stable on detector scales

LLPs in the SM



LLPs

LLPs in the SM

- Many particles of the SM are long-lived
- Some are even stable on detector scales

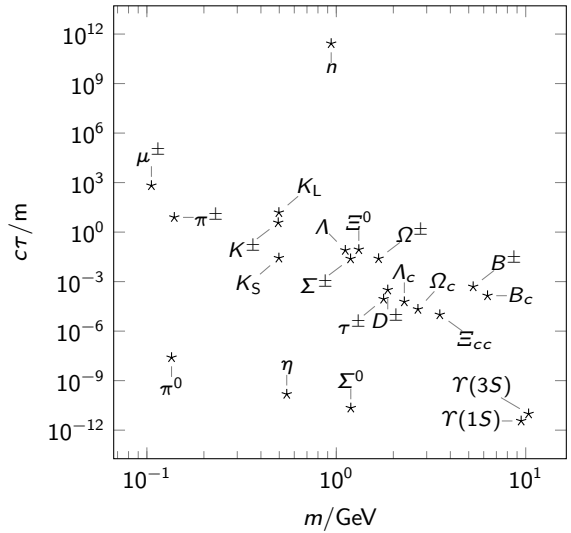
Portals to hidden sectors

- Many SM extensions feature hidden sectors
- Often motivated by DM candidates
- A key signature of such models are LLPs

Prime examples

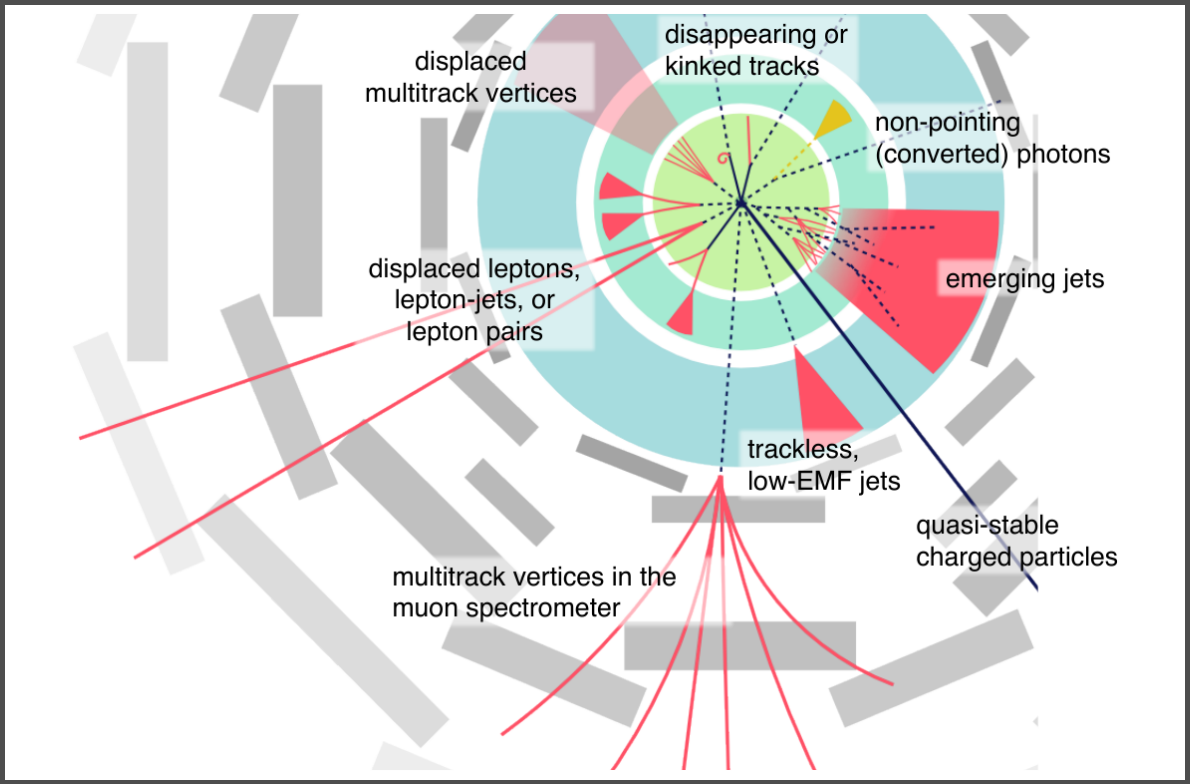
- Axion-like particles (ALPs)
- Heavy Neutral Leptons (HNLs)
  Right Handed Neutrinos (RHNs)
- Hidden U(1) / New gauge bosons

LLPs in the SM



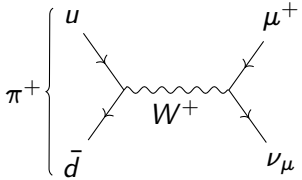
LLP signatures

[1903.04497]



Longevity in the SM

$\pi^+ \to \mu^+ \nu_\mu$



Charged pion

- Decay via weak interactions
- Decay extremely off-shell

$$\Gamma_{\pi^+} \propto g_W^2 \left(\frac{m_\pi}{m_W} \right)^4 m_\pi$$

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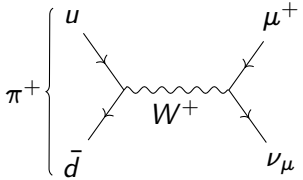
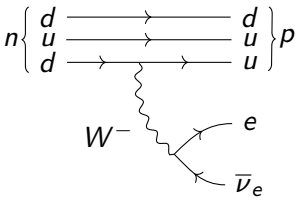


$n \to p e \overline{\nu}_e$



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Neutron

- Proton and neutron are almost mass degenerate due to isospin
- Decay extremely off-shell

$$\Gamma_n \propto g_W^2 \left(\frac{\Delta_{np}}{m_W} \right)^4 \Delta_{np} \ , \quad \Delta_{np} = m_n - m_p$$

Longevity in the SM

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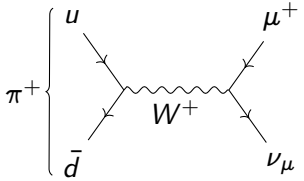

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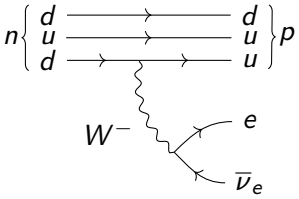
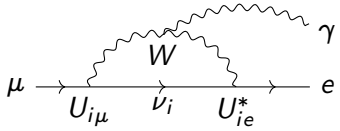


$\mu \to e\gamma$



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$$\Gamma_{\pi^+} \propto g_W^2 \left(\frac{m_\pi}{m_W} \right)^4 m_\pi$$

Muon

- Flavour changing neutral current
- Lepton flavour only violated by neutrino masses and Yukawa couplings

$$\mathrm{BR}(\mu \to e\gamma) \propto 10^{-13}$$

Neutron

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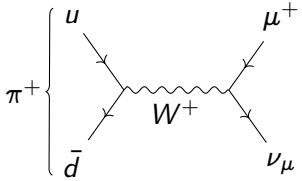

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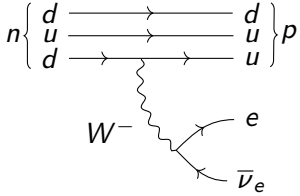

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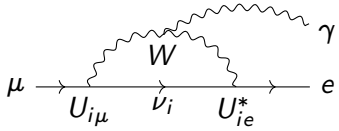

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Generically

- Off-shell decay
- Small mass splitting
- Small coupling (hierarchy or loop suppression)

$$\Gamma \propto \lambda^2 \left(\frac{m}{M}\right)^n m$$

Axion like particles (ALP)

The ALP mass and interaction terms

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

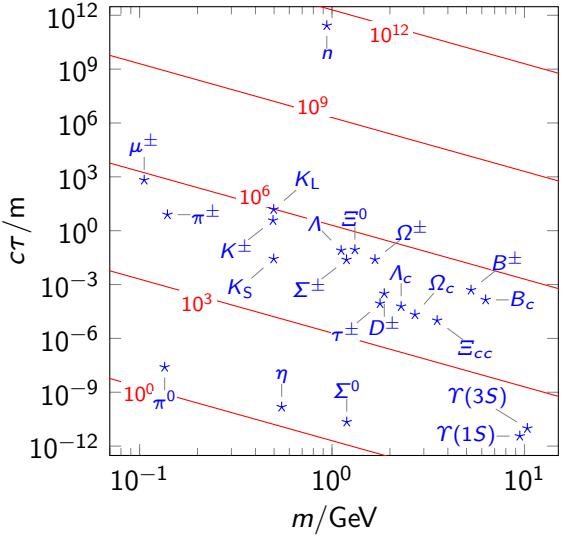
With a model dependent constant c.

Widths

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

With NLO correction factor k.

ALPs lifetime



SM particles and ALP decay constant f_a/GeV

Heavy neutral leptons (HNLs)

Right handed neutrinos

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

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

Electroweak symmetry breaking

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

Seesaw mechanism

$$m_\nu = -m_{ai} M^{-1}_{ij} m^T_{bj} = -\theta_{ai} M_{ij} \theta^T_{bj}$$

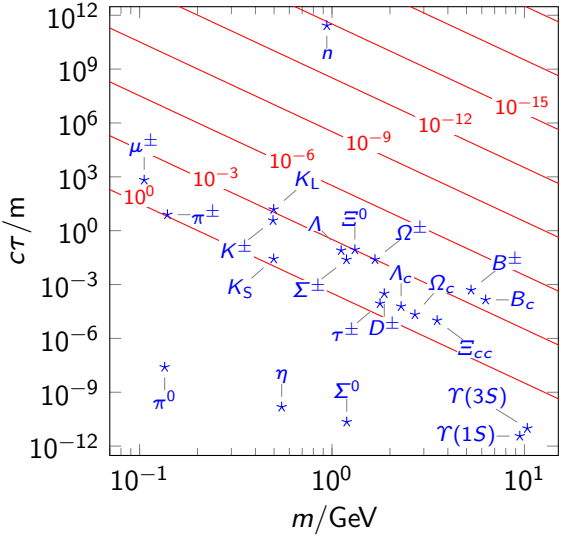
$$\theta_{ai} = m_{aj} M^{-1}_{ij}$$

produces tiny SM neutrino masses

Decay width

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

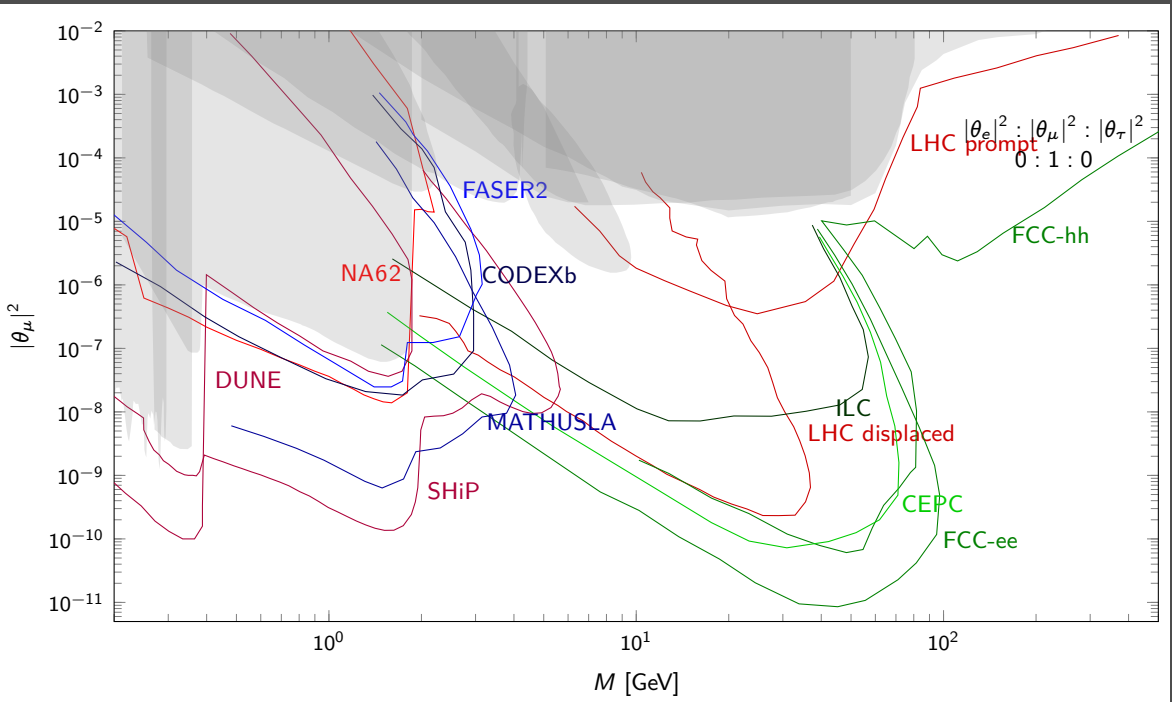
HNL lifetime



SM particles and HNL coupling $|\theta|^2$

HNL discovery potential

[2011.01005; 1903.06100; 1801.04207]



Portal effective theories (PETs)

Effective theories of Standard Model fields

Effective field theories

- includes all fields of interest
- consists of all operators allowed by symmetry of the theory
- non-renormaliseable operators encode heavy new physics (NP)

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

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Standard Model EFT

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

Light EFT

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

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Chiral perturbation theory

- exploits U(3) flavour symmetry
- light meson interactions

Heavy quark EFT

- 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

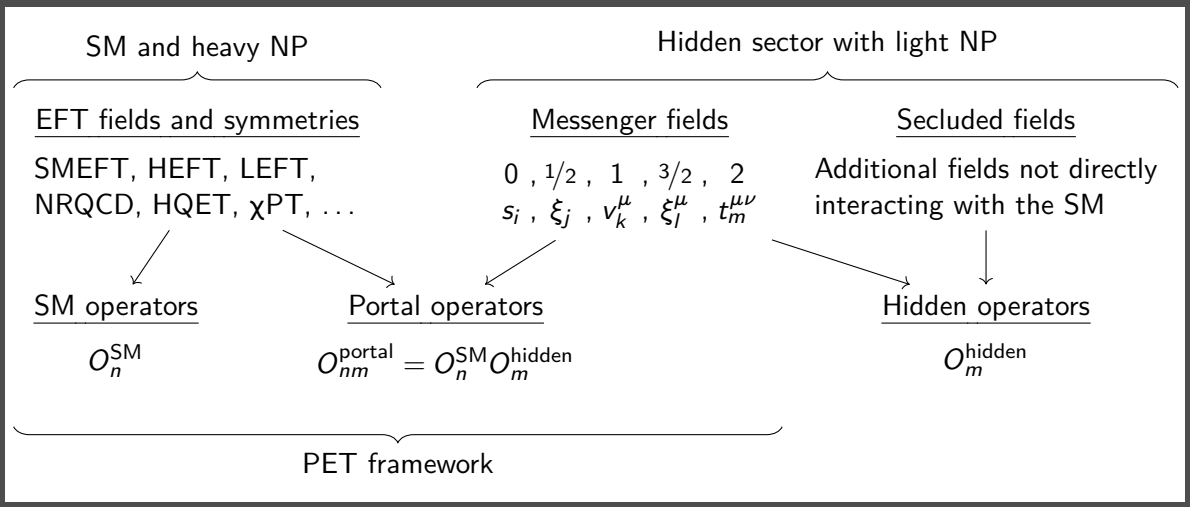
- contains messenger fields
- can entail a complicated secluded sector

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

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

Hidden operators

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

Form portal operators

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

Can be collected in Portal currents

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

Capturing the portal interactions of the SM

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

For example: The axial anomaly

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

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

In terms of current θ and operator w

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

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	Gauge bosons
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	$v_\mu v^\mu \lvert H\rvert^2$ $\partial_\mu v^\mu \lvert H\rvert^2$ $v^\mu H^\dagger \overleftrightarrow{D}_\mu H$		$v^\mu q_a^\dagger \overline{\sigma}_\mu q_b$ $v^\mu \overline{u}_a^\dagger \sigma_\mu \overline{u}_b$ $v^\mu \overline{d}_a^\dagger \sigma_\mu \overline{d}_b$ $v^\mu \ell_a^\dagger \overline{\sigma}_\mu \ell_b$ $v^\mu \overline{e}_a^\dagger \sigma_\mu \overline{e}_b$	

Portal SMEFT operators

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Non-renormaliseable operators

	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

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

Individual parts

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

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

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

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

Portal SMEFT

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

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

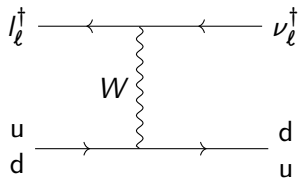
Portal LEFT current Lagrangian

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

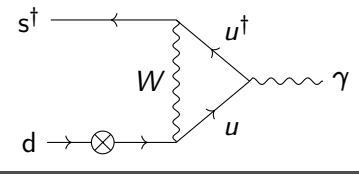
The currents are constant in the SM but can contain dynamical NP contributions.

EW induced portal LEFT currents

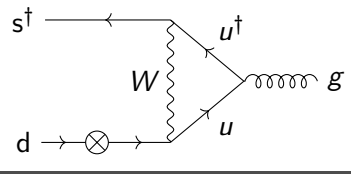
Vector current interactions



Electromagnetic dipole



Chromomagnetic dipole



QCD operators and portal currents

SM operator	current	
$\boldsymbol{Q}^{\mu\,b}_{\ a} = q_a \sigma^\mu q^{b\dagger}$	$\boldsymbol{L}^\mu = \boldsymbol{l}^\mu + \boldsymbol{V}_l^\mu$	left-handed
$\overline{\boldsymbol{Q}}^{\mu\,\dot{b}}_{\ \dot{a}} = \overline{q}^\dagger_{\dot{a}} \overline{\sigma}^\mu \overline{q}^{\dot{b}}$	$\boldsymbol{R}^\mu = \boldsymbol{r}^\mu + \boldsymbol{V}_r^\mu$	right-handed
$\boldsymbol{Q}_{\mu\nu\,a}^{\ \ \ \dot{a}} = q_a \sigma_{\mu\nu} \overline{q}^{\dot{a}}$	$\boldsymbol{T}^{\mu\nu} = \boldsymbol{\tau}^{\mu\nu} + \boldsymbol{T}_\tau^{\mu\nu}$	tensorial
$\widetilde{\boldsymbol{Q}}^{\dot{a}}_{\ a} = q_a \sigma_{\mu\nu} G^{\mu\nu} \overline{q}^{\dot{a}}$	$\boldsymbol{\Gamma} = \boldsymbol{\gamma} + \boldsymbol{S}_\gamma$	chromomagnetic

Electroweak contributions to the portal LEFT current Lagrangian

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

The SM parts of the currents

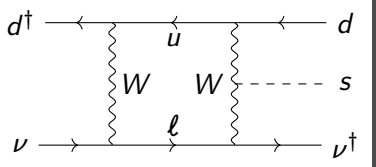
are either constant or contain the photon contribution

Not shown here

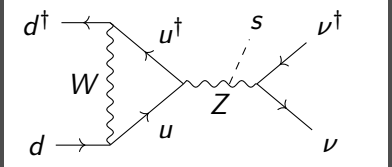
4-quark operators

Portal LEFT operators

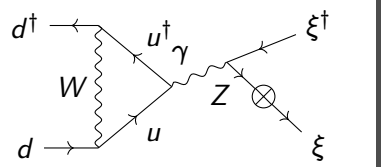
Scalar box diagram



Scalar penguin diagram



Fermionic penguin diagram



Quark flavour conserving operators

	d	Scalar	Vector	Gauge
s_i	4	$s_i\ \overline{\psi}\psi$		
	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	$\xi_a\ \nu$		
	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	$s_i s_j s_k\ \overline{d}d$ $\partial^2 s_i\ \overline{d}d$ $s_i\partial_\mu s_j\ d^\dagger\overline{\sigma}^\mu d$	$s_i\ F^{\mu\nu}\overline{d}\sigma_{\mu\nu}d$ $s_i\ G^{\mu\nu}\overline{d}\sigma_{\mu\nu}d$	
	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 interactions of mesons

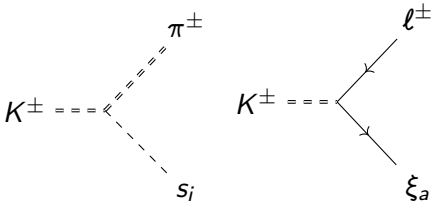
Portal LEFT

serves as starting point for portal EFTs of mesons

Interactions of light mesons with messengers

- Kaon decay into hidden sectors
- detectable *e.g.* in Kaon factories such as NA62

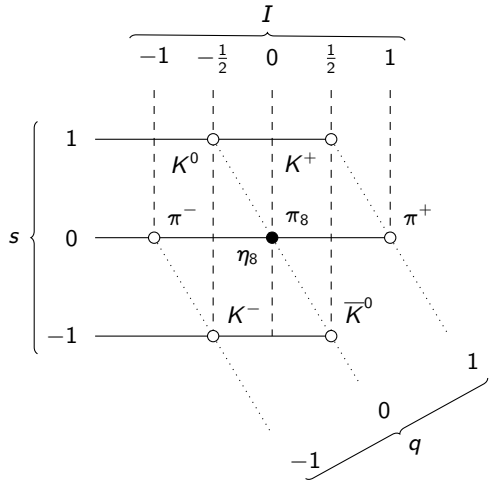
Meson decay into hidden sectors



See dedicated talk by Philipp Klose

in the same session

Portal chiral perturbation theory



Conclusion

- New Physics might be found in hidden sectors
- The messenger particle can easily be long-lived
- EFTs are designed to describe heavy New Physics
- We have extended EFTs of the SM to include also portals to hidden sectors

	d	Higgs	Yukawa + h.c.	Fermions	Gauge bosons
	4		$\xi^\dagger_{a\mu}\overline{\sigma}^\mu \ell_b \widetilde{H}^\dagger$		
ξ^a_μ + h.c.	5	$\xi_{a\mu}\xi^\mu_b \lvert H\rvert^2$ $\xi_{a\mu}\sigma^{\mu\nu}\xi_{b\nu}\lvert H\rvert^2$	$(\partial^\mu \xi_{a\mu})\ell_b \widetilde{H}^\dagger$ $(\partial_\nu \xi_{a\mu})\overline{\sigma}^{\mu\nu}\ell_b \widetilde{H}^\dagger$ $\xi_{a\mu}\ell_b D^\mu \widetilde{H}^\dagger$ $\xi_{a\mu}\overline{\sigma}^{\mu\nu}\ell_b D_\nu \widetilde{H}^\dagger$		$\xi_{a\mu}\xi_{b\nu}B^{\mu\nu}$ $\xi_{a\rho}\sigma^{\mu\nu}\xi^\rho_b B_{\mu\nu}$ $\xi_{a\mu}\sigma^{\mu\rho}\xi^\nu_b B_{\nu\rho}$ $\xi_{a\mu}\sigma^{\mu\rho}\xi^\nu_b \widetilde{B}_{\nu\rho}$ $\xi_{a\alpha}\sigma^\rho_\mu \xi_{b\beta} B_{\nu\rho}\epsilon^{\alpha\beta\mu\nu}$
$t_{\mu\nu}$	3				$t_{\mu\nu}B^{\mu\nu}$ $\widetilde{t}_{\mu\nu}B^{\mu\nu}$
	5	$t^{\mu\nu}D_\mu H^\dagger D_\nu H$ $\widetilde{t}^{\mu\nu}D_\mu H^\dagger D_\nu H$ $(\partial_\mu t^{\mu\nu})(H^\dagger \overleftrightarrow{D}_\nu H)$	$t^{\mu\nu}\boldsymbol{q_a}\boldsymbol{\sigma_{\mu\nu}}\boldsymbol{u_b}\widetilde{H}$ $t^{\mu\nu}\boldsymbol{q_a}\boldsymbol{\sigma_{\mu\nu}}\boldsymbol{d_b}H$ $t^{\mu\nu}\ell_a\sigma_{\mu\nu}e_b H$	$(\partial^\mu t_{\mu\nu})\boldsymbol{q}^\dagger_{\boldsymbol{a}}\overline{\boldsymbol{\sigma}}^{\boldsymbol{\nu}}\boldsymbol{q_b}$ $(\partial^\mu t_{\mu\nu})\boldsymbol{u}^\dagger_{\boldsymbol{a}}\boldsymbol{\sigma}^{\boldsymbol{\nu}}\boldsymbol{u_b}$ $(\partial^\mu t_{\mu\nu})\boldsymbol{d}^\dagger_{\boldsymbol{a}}\boldsymbol{\sigma}^{\boldsymbol{\nu}}\boldsymbol{d_b}$ $(\partial^\mu t_{\mu\nu})\ell^\dagger_a\overline{\sigma}^\nu\ell_b$ $(\partial^\mu t_{\mu\nu})e^\dagger_a\sigma^\nu e_b$ $(\partial^\mu \widetilde{t}_{\mu\nu})\boldsymbol{q}^\dagger_{\boldsymbol{a}}\overline{\boldsymbol{\sigma}}^{\boldsymbol{\nu}}\boldsymbol{q_b}$ $(\partial^\mu \widetilde{t}_{\mu\nu})\boldsymbol{u}^\dagger_{\boldsymbol{a}}\boldsymbol{\sigma}^{\boldsymbol{\nu}}\boldsymbol{u_b}$ $(\partial^\mu \widetilde{t}_{\mu\nu})\boldsymbol{d}^\dagger_{\boldsymbol{a}}\boldsymbol{\sigma}^{\boldsymbol{\nu}}\boldsymbol{d_b}$ $(\partial^\mu \widetilde{t}_{\mu\nu})\ell^\dagger_a\overline{\sigma}^\nu\ell_b$ $(\partial^\mu \widetilde{t}_{\mu\nu})e^\dagger_a\sigma^\nu e_b$	$t_{\mu\nu}\boldsymbol{G}^{\boldsymbol{\mu\rho}}\boldsymbol{G}^{\boldsymbol{\nu}}_{\boldsymbol{\rho}}$ $\widetilde{t}_{\mu\nu}\boldsymbol{G}^{\boldsymbol{\mu\rho}}\boldsymbol{G}^{\boldsymbol{\nu}}_{\boldsymbol{\rho}}$ $t_{\mu\nu}\widetilde{\boldsymbol{G}}^{\boldsymbol{\mu\rho}}\boldsymbol{G}^{\boldsymbol{\nu}}_{\boldsymbol{\rho}}$ $t_{\mu\nu}\boldsymbol{G}^{\boldsymbol{\mu\rho}}\widetilde{\boldsymbol{G}}^{\boldsymbol{\nu}}_{\boldsymbol{\rho}}$ $t_{\mu\nu}W^{\mu\rho}W^\nu_\rho$ $t_{\mu\nu}\widetilde{W}^{\mu\rho}W^\nu_\rho$ $t_{\mu\nu}W^{\mu\rho}\widetilde{W}^\nu_\rho$ $\widetilde{t}_{\mu\nu}B^{\mu\rho}B^\nu_\rho$ $t_{\mu\nu}\widetilde{B}^{\mu\rho}B^\nu_\rho$ $t_{\mu\nu}B^{\mu\rho}\widetilde{B}^\nu_\rho$ $t_{\mu\nu}B^{\mu\nu}\lvert H\rvert^2$ $\widetilde{t}_{\mu\nu}B^{\mu\nu}\lvert H\rvert^2$

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