Techniques for model-independent Interpretations of Light Hidden Particle Searches

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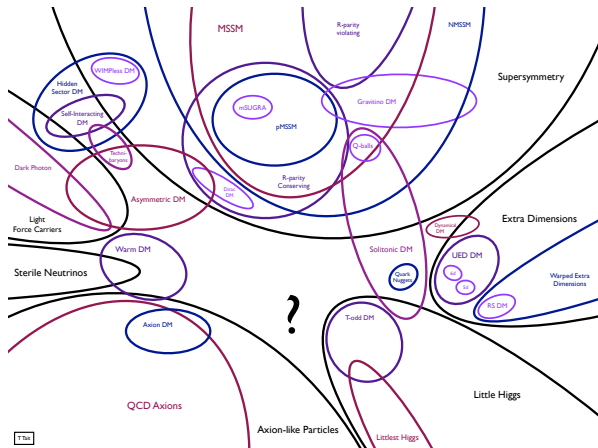
Workshop on Feebly Interacting Particles 2022

based on
arXiv:2105.06477 / arXiv:2203.02229
Published in Collaboration with Chiara Arina, Jan Hajer

Effective Field Theories: Good But Not Perferct

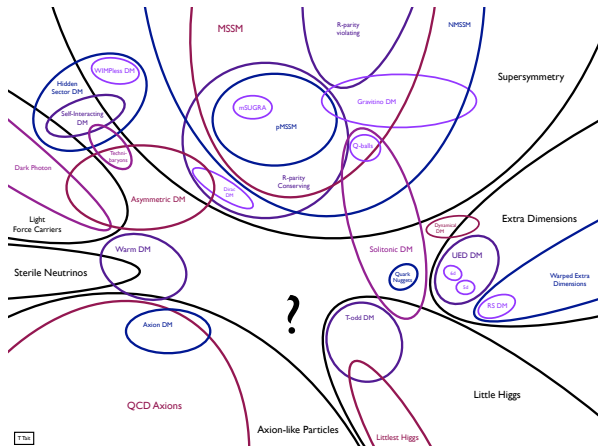- EFTs fine for heavy new physics (NP)

Made by T. Tait, see arXiv:1401.6085

What about more complicated, realistic hidden sectors?
⇒ Use factorization!

Effective Field Theories: Good But Not Perferct

- EFTs fine for heavy new physics (NP)

- EFTs, simplified models for light NP useful but simplistic

Made by T. Tait, see arXiv:1401.6085

What about more complicated, realistic hidden sectors?
⇒ Use factorization!

Small Portal Couplings Ensure Factorization

■ Most general SM extension:

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \mathcal{L}_{\mathsf{hidden}} + \epsilon \mathbf{A}_d \mathbf{B}^d$$

$\mathbf{A}_d$ = SM operator / $\mathbf{B}^d$ = hidden operator / ϵ = coupling / $d \geq 4$ allowed

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$$\Gamma\left(\text{SM} \to \text{SM'} + \text{hidden}\right) \propto \epsilon^2 \mathbf{M}_d \mathbf{M}_e^\dagger \mathbf{J}^{de} + \mathcal{O}\left(\epsilon^3\right) \quad \mathbf{J}^{de} = \sum \mathbf{J}^d \mathbf{J}^{e\dagger}$$

  $\uparrow$
  Indistinguishable final states

  $\mathbf{M}$ = reduced matrix elements (SM only, model-independent)
  $\mathbf{J}$ = hidden currents (hidden only, signature-independent)

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See arXiv:2203.02229

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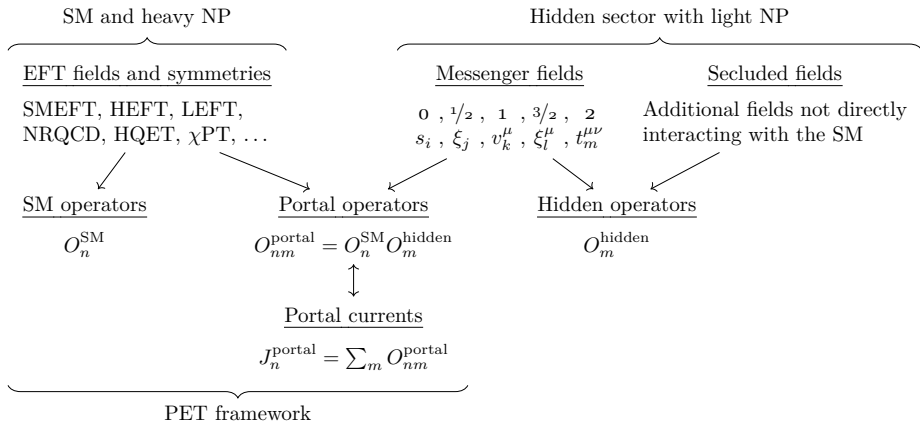$\boldsymbol{M}$ = reduced matrix elements (SM only, model-independent)
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2 With portal EFTs: Model-independent constraints

PETs maximize Model-independence

We developed framework to construct **portal effective theories (PETs)** that couple SM EFTs to generic hidden sectors

SM and heavy NP

EFT fields and symmetries

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

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

SM operators

O_n^{SM}

Portal operators

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

$\updownarrow$

Portal currents

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

Hidden operators

O_m^{hidden}

PET framework

Application: Generic meson interaction rates

- Light meson experiments efficiently constrain hidden sectors (NA62, MaTHUSLA, KOTO, *etc.*)

Integrating out heavy fields   Spurion analysis   Expansion

```
┌──────────────────┐     ┌──────────────────┐     ┌──────────────────┐     ┌──────────────────┐
│  Portal SMEFTs   │     │  Portal LEFTs    │     │  Portal χPTs     │     │  Feynman rules   │
│   (d ≤ 5)        │     │   (d ≤ 7)        │     │   (NLO)          │     │                  │
└──────────────────┘     └──────────────────┘     └──────────────────┘     └──────────────────┘
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Portal SMEFTs ($d \leq 5$)

Portal LEFTs ($d \leq 7$)

Portal χPTs (NLO)

Feynman rules

EWSB

Coefficient matching

Golden processes
$$K^{\pm} \to \pi^{\pm} s$$
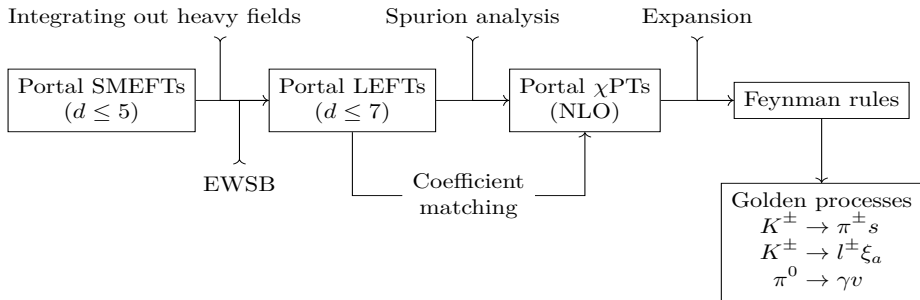$$K^{\pm} \to l^{\pm} \xi_a$$
$$\pi^0 \to \gamma v$$

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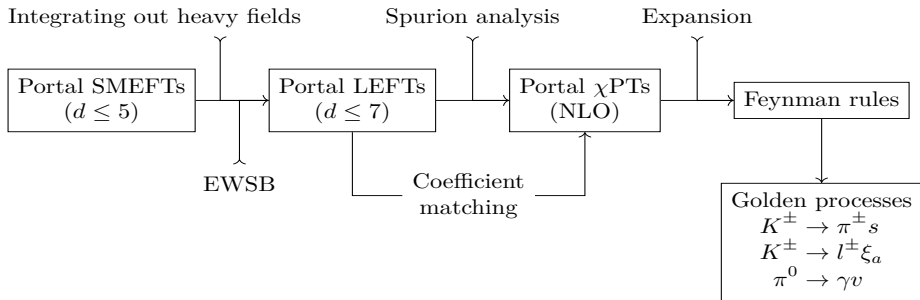- Light meson experiments efficiently constrain hidden sectors (NA62, MaTHUSLA, KOTO, *etc.*)

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- We constructed **portal SMEFTs** / **LEFTs** / **ChPTs** ($S = 0, 1/2, 1$ messengers / $\Delta F \neq 0$ allowed / all leading portal operators)

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■ We computed benchmark master decay rates
($\pi^0 \to \gamma \, v$ / $K^+ \to \pi^+ s$ / $K^+ \to \ell^+ +$ anything)

Summary and Outlook

1 Hidden Particle Production Rates Factorize via

$$\Gamma\left(\text{SM} \to \text{SM' + hidden}\right) \propto \epsilon^2 \, \boldsymbol{M_d} \, \boldsymbol{M_e^\dagger} \, \boldsymbol{J^{de}} + \mathcal{O}\left(\epsilon^3\right)$$

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Future work

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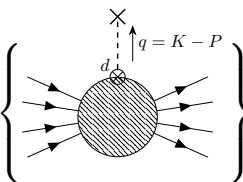(single spin 0, $1/2$, 1 messenger, $\Delta F \neq 0$ allowed)

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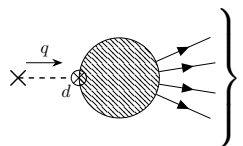($\pi^0 \to \gamma \, v$ / $K^+ \to \pi^+ s$ / $K^+ \to \ell^+ +$ anything)

Future work

- Factorizing decay / scattering / finite temperature rates
- PETs for heavy mesons, (p)NRQED *etc.*
- Computing interaction rates, hidden currents + automation

Thank you for your attention!

M_d, J^d are Feynman Diagram Sums

$$\mathrm{i}\, M_d = \mathcal{K} \left\{ \hspace{3cm} \right\} \mathcal{P} \qquad\qquad \mathrm{i}\, J_d = \hspace{3cm} \left\{ \hspace{2cm} \right\} \mathcal{Q}$$

EW Scale PETs: Portal Operators

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

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

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

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:

$$\delta\mathcal{L}_{\text{QCD}} \rightarrow -q^\dagger \overline{\sigma}_\mu \boldsymbol{L}^\mu q - \overline{q}\sigma_\mu \boldsymbol{R}^\mu \overline{q}^\dagger - \Omega\, G_{\mu\nu}G^{\mu\nu} - \Theta\, G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$-\left[\overline{q}\boldsymbol{M}q + \overline{q}\,\overline{\sigma}^{\mu\nu}\,\boldsymbol{T}_{\mu\nu}q - \overline{q}\,\boldsymbol{\Gamma}\overline{\sigma}^{\mu\nu}G_{\mu\nu}q + \text{h.c.}\right] + \mathcal{L}_{\overline{q}q\overline{q}q}[H_l, H_r, H_s]$$

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)

1) Model-independent $\pi^0 \to \gamma v_i$ 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:

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

2) $K^+ \to \pi^+ s_i$ Portal Interactions

Currents:

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

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

Scalar current coupling to Kaons:

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

where

$$c_{K\pi s_i} = \mathrm{Re}\, \boldsymbol{c}_i^{S_m d}{}_s + \frac{\epsilon_{\mathsf{EW}}}{2} \left((m_K^2 - m_\pi^2)\, \mathrm{Re}\, \boldsymbol{c}_i^{S_m u}{}_u + m_K^2\, \mathrm{Re}\, \boldsymbol{c}_i^{S_m d}{}_d - m_\pi^2\, \mathrm{Re}\, \boldsymbol{c}_i^{S_m s}{}_s \right) \theta_{K^\pm \pi^\mp}$$

$$-\frac{\epsilon_{\mathsf{EW}}}{2} \left(2 v h_b \left(\frac{m_{ud}}{m_s} \left(\boldsymbol{c}_i^{S_m d}{}_d - \boldsymbol{c}_i^{S_m s}{}_s{}^\dagger \right) + \boldsymbol{c}_i^{S_m d}{}_d{}^\dagger \right) + \frac{m_{ud} + m_s}{v} h_{bi} - \kappa_\gamma \left(c_{i\bar{d}s}^\gamma + c_{i\bar{s}d}^{\gamma\dagger} \right) \right)$$

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

2) Model-independent $K^+ \to \pi^+ s_i$ Amplitude

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

where

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

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

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

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

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

- 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

3) Factorization example: $K^+ \to \ell^+ + \text{anything}$

- Relevant portal interactions (see arXiv:2105.06477):

$$\mathcal{L}_{\text{portal}} \supset \underbrace{v \; \nu \; \boldsymbol{B}_\nu + \frac{V_{\text{us}}}{v^2}(s^\dagger \overline{\sigma}_\mu u)(\boldsymbol{B}_\ell^\dagger \overline{\sigma}^\mu \ell)}_{n=2 \text{ portal operators}} \quad \Rightarrow \quad \begin{array}{l} \text{Two portal vertices} \\ (\text{Missing mass } q^2) \end{array}$$

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■ Compute M_ℓ / M_ν $\Rightarrow$ Master decay rate:

$$\frac{\mathrm{d}}{\mathrm{d}x_q} \frac{\Gamma\left(K^+ \to \ell^+ + \text{NP}\right)}{\Gamma\left(K^+ \to \ell^+ + \nu\right)} = \frac{\rho(x_q)}{\rho(0)} \underbrace{\frac{1}{2\pi x_q} \text{tr}_D \left\{ \not{q} \boldsymbol{J}^{\ell\ell} - 2\,\mathrm{Re}\, v \boldsymbol{J}^{\ell\nu} + \frac{\not{q}}{q^2} v^2 \boldsymbol{J}^{\nu\nu} \right\}}_{= \frac{F(x_q)}{2\pi}}$$

$\rho(x_q)$ is phase-space factor

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$\rho(x_q)$ is phase-space factor

Use constraints on $F(x_q)$ to compare and contrast different models!

3) Re-interpreting a prior HNL search

(See also arXiv:2005.09575)

Master decay rate:

$$\frac{\mathrm{d}}{\mathrm{d}x_q}\frac{\Gamma\left(K^+ \to \ell^+ + \mathrm{NP}\right)}{\Gamma\left(K^+ \to \ell^+ + \nu\right)} = \frac{\rho(x_q)}{\rho(0)}\underbrace{\frac{1}{2\pi x_q}\mathrm{tr}_D\left\{\slashed{q}\,\boldsymbol{J}^{\ell\ell} - 2\,\mathrm{Re}\,v\,\boldsymbol{J}^{\ell\nu} + \frac{\slashed{q}}{q^2}v^2\,\boldsymbol{J}^{\nu\nu}\right\}}_{=\frac{F(x_q)}{2\pi}}$$

General form factor structure:

$$\frac{F(x)}{2\pi} = \sum_i A_i\delta(x - x_i) + B \qquad\qquad x_i = \frac{m_i^2}{m_K^2}$$

Resulting bounds:

$$\rho(x_e, x_i)A_i \lesssim 7 \cdot 10^{-11} \qquad\qquad \rho(x_e, x_q)B(x_q) \lesssim 2 \cdot 10^{-4}$$

3) HNL Hidden Currents

$$B_d = \sum_i c_{di} \xi_i \qquad\qquad d = \nu, \ell$$

$$J_{\dot\beta\alpha}^{\nu\nu} = \sum_i \frac{c_{\nu i}^\dagger c_{\nu i}}{2\omega_i} (q_i^\mu \overline{\sigma}_\mu)_{\dot\beta\alpha} \overline{\delta}(q_0 - \omega_i) \qquad J_{\beta\alpha}^{\ell\nu} = \sum_i \frac{c_{\ell i}^\dagger c_{\nu i}}{2\omega_i} m_i \epsilon_{\beta\alpha} \overline{\delta}(q_0 - \omega_i)$$

$$J_{\beta\dot\alpha}^{\ell\ell} = \sum_i \frac{c_{\ell i}^\dagger c_{\ell i}}{2\omega_i} (q_i^\mu \sigma_\mu)_{\beta\dot\alpha} \overline{\delta}(q_0 - \omega_i)$$

$$\frac{F_\ell(x_q)}{2\pi} = \sum_i U_i^2 \Theta(q_0) \delta(x_q^2 - x_i^2) \qquad x_i = \frac{m_i^2}{m_K^2} \qquad U_i^2 = \left| c_{\ell i} - \frac{v c_{\nu i}}{m_i} \right|^2$$