Factorizing Hidden Particle Production Rates

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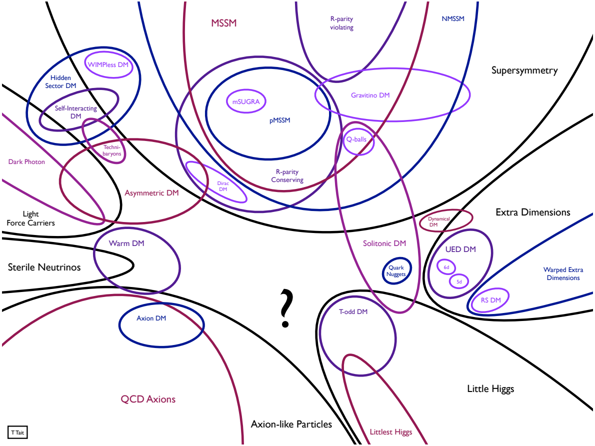
Searching for long-lived particles at the LHC and beyond: Eleventh workshop of the LLP Community

based on
arXiv:2203.02229

Factorization helps constraining hidden sectors

- Large model zoo
- EFTs and simplified models: Good but not perfect



Made by T. Tait, see arXiv:1401.6085

What about more complicated, realistic hidden sectors?
$\Rightarrow$ Use factorization!

Small Portal Couplings Ensure Factorization

- Most general SM extension:

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

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

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

↑ Indistinguishable final states

$\boldsymbol{M}$ = reduced matrix elements (SM only, model-independent)

$\boldsymbol{J}$ = hidden currents (hidden only, signature-independent)

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2. With portal EFTs: Model-independent constraints

Example computation: $K^+ \to \ell^+ + \text{NP}$ decays

1. Relevant portal interactions (see arXiv:2105.06477):

$$\mathcal{L}_{\text{portal}} \supset \underbrace{v\ \nu\, \boldsymbol{B}_\nu + \frac{V_{\text{us}}}{v^2}(s^\dagger \overline{\sigma}_\mu u)(\boldsymbol{B}_\ell^\dagger \overline{\sigma}^\mu \ell)}_{n=2 \text{ portal operators}} \quad \Rightarrow$$

Two portal vertices (Missing mass q^2)

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2. Compute M_ℓ / M_ν $\Rightarrow$ Master decay rate:

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

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

Summary and Outlook

1. Hidden Particle Production Rates Factorize

$$\Gamma\left(\mathrm{SM} \to \mathrm{SM'} + \mathrm{NP}\right) \propto \epsilon^2 \boldsymbol{M}_d \boldsymbol{M}_e^\dagger \boldsymbol{J}^{de} + \mathcal{O}\left(\epsilon^3\right)$$

   - Simplifies adapting rates to new models, observables
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2. Most general $K^+ \to \ell^+ + \mathrm{NP}$ decay rate

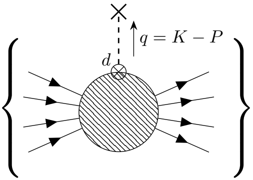
$$\frac{\mathrm{d}}{\mathrm{d}x_q} \frac{\Gamma\left(K^+ \to \ell^+ + \mathrm{NP}\right)}{\Gamma\left(K^+ \to \ell^+ + \nu\right)} = \frac{\rho(x_q)}{\rho(0)} \frac{F(x_q)}{2\pi}$$

Future work

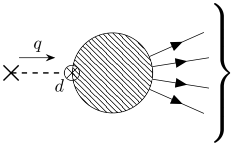
- Factorization of scattering / finite temperature rates
- Compute lots of production rates, hidden currents

Thank you for your attention!

M_d, J^d are standard Feynman diagram sums

$\mathrm{i}\, M_d = \mathcal{K}$ 

$\mathcal{P}$

$\mathrm{i}\, J_d =$ 

$\mathcal{Q}$

Portal Effective Theory Framework

SM and heavy NP

EFT fields and symmetries

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

Hidden sector with light NP

Messenger fields

$$\begin{array}{ccccc} 0 & 1/2 & 1 & 3/2 & 2 \\ s_i, & \xi_j, & v_k^\mu, & \xi_l^\mu, & t_m^{\mu\nu} \end{array}$$

Secluded fields

Additional fields not directly interacting with the SM

SM operators

$$O_n^{\text{SM}}$$

Portal operators

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

Hidden operators

$$O_m^{\text{hidden}}$$

Portal currents

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

PET framework

Re-interpreting a prior HNL search (see arXiv:2005.09575)

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:

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

HNL Hidden Currents

$$\boldsymbol{B}_d = \sum_i c_{di}\xi_i \qquad\qquad d = \nu, \ell$$

$$J^{\nu\nu}_{\dot\beta\alpha} = \sum_i \frac{c^\dagger_{\nu i} c_{\nu i}}{2\omega_i}(q_i^\mu \overline{\sigma}_\mu)_{\dot\beta\alpha} 2\pi\delta(q_0 - \omega_i)$$

$$J^{\ell\nu}_{\beta\alpha} = \sum_i \frac{c^\dagger_{\ell i} c_{\nu i}}{2\omega_i} m_i \epsilon_{\beta\alpha} 2\pi\delta(q_0 - \omega_i)$$

$$J^{\ell\ell}_{\beta\dot\alpha} = \sum_i \frac{c^\dagger_{\ell i} c_{\ell i}}{2\omega_i}(q_i^\mu \sigma_\mu)_{\beta\dot\alpha} 2\pi\delta(q_0 - \omega_i)$$

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

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