Techniques for model-independent Interpretations of Light Hidden Particle Searches

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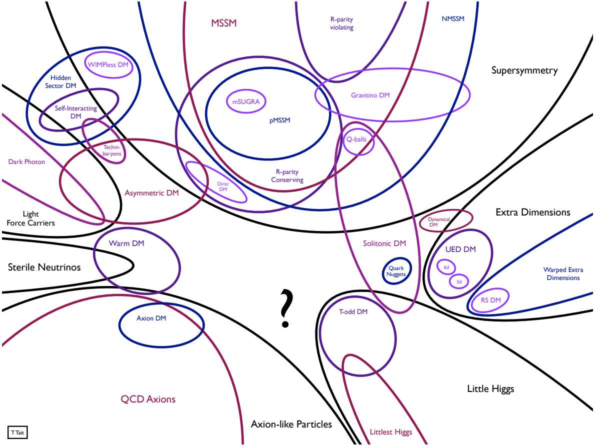
based on
arXiv:2105.06477 / arXiv:2203.02229
Published in Collaboration with Chiara Arina, Jan Hajer

Effective Field Theories: Good But Not Perferct

- EFTs fine for heavy new physics (NP)

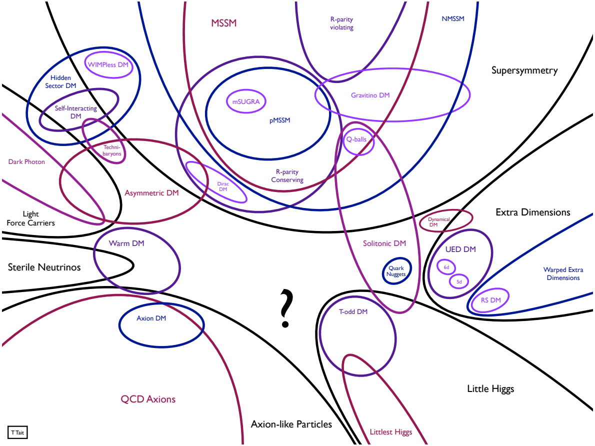


Made by T. Tait, see arXiv:1401.6085

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



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

Small Portal Couplings Ensure Factorization

See arXiv:2203.02229

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

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

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2. With portal EFTs: Model-independent constraints

PETs maximize Model-independence

See arXiv:2105.06477

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

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

Secluded fields

Additional fields not directly interacting with the SM

SM operators

O_n^{SM}

Portal operators

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

$\updownarrow$

Portal currents

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

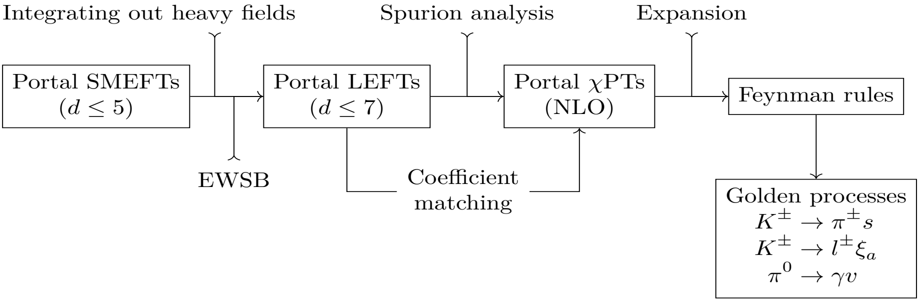
Hidden operators

O_m^{hidden}

PET framework

Application: Generic meson interaction rates

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



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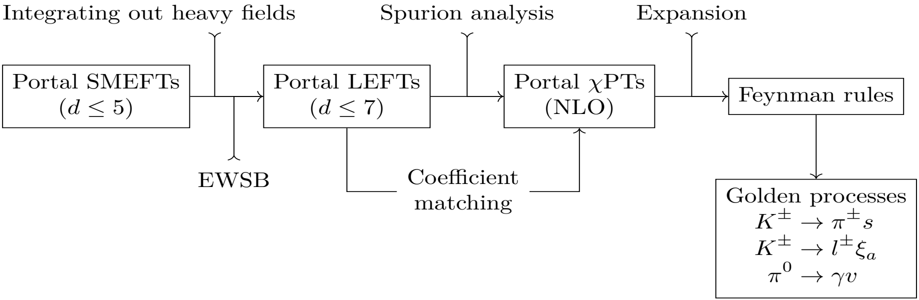

- We constructed **portal SMEFTs** / **LEFTs** / **ChPTs** ($S = 0, 1/2, 1$ messengers / $\Delta F \neq 0$ allowed / all leading portal operators)

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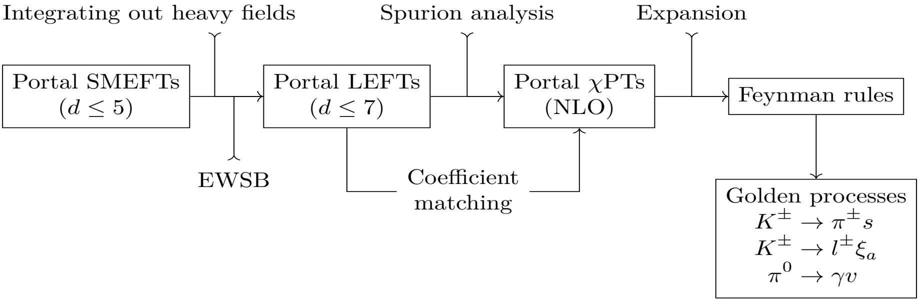

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- We computed benchmark master decay rates ($\pi^0 \to \gamma\ v$ / $K^+ \to \pi^+ s$ / $K^+ \to \ell^+ +$ anything)

Summary and Outlook

1. Hidden Particle Production Rates Factorize via

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

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Future work

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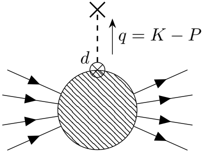
Future work

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

Thank you for your attention!

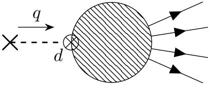
M_d, J^d are Feynman Diagram Sums

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



$\Big\} \mathcal{P}$

$\mathrm{i}\, J_d =$



$\Big\} \mathcal{Q}$

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	$s_i s_j s_k \|H\|^2$ $s_i D^\mu H^\dagger D_\mu H$ $s_i \|H\|^4$	$s_i q_a \overline{u}_b \widetilde{H}^\dagger$ $s_i q_a \overline{d}_b H^\dagger$ $s_i \ell_a \overline{e}_b H^\dagger$		$s_i G^a_{\mu\nu} G_a^{\mu\nu}$ $s_i W^a_{\mu\nu} W_a^{\mu\nu}$ $s_i B_{\mu\nu} B^{\mu\nu}$ $s_i G^a_{\mu\nu} \widetilde{G}_a^{\mu\nu}$ $s_i W^a_{\mu\nu} \widetilde{W}_a^{\mu\nu}$ $s_i B_{\mu\nu} \widetilde{B}^{\mu\nu}$
ξ_a + h.c.	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	$\xi_a^\dagger \overline{\sigma}_\mu\, e d^\dagger \overline{\sigma}^\mu u$ $\xi_a^\dagger \overline{\sigma}_\mu\, \nu d^\dagger \overline{\sigma}^\mu d$		

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)

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:

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

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

Currents:

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

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

Scalar current coupling to Kaons:

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

where

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

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

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

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

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

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

- Relevant portal interactions (see arXiv:2105.06477):

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

Two portal vertices (Missing mass q^2)

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Two portal vertices
(Missing mass q^2)

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

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

$\rho(x_q)$ 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:

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

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

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

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

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

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