CHARTING THE FIFTH FORCE LANDSCAPE

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Abstract

We propose a new framework for exploring dark forces, in which the effects of *any* general scalar fifth force are captured by a single, positive-definite spectral function. In this language, all experimental observables can be expressed in completely general terms, facilitating the straightforward extraction of limits to any specific model. This framework also opens the possibility to probe violations of QFT fundamentals within hidden sectors.

Motivation

- Dark Matter remains elusive on a particle level
- The first tools for exploring the SM came from photons and neutrinos
- Could light neutral states from hidden sectors unlock the Dark Sector?
- Exchange of new light states between ordinary nucleons generates a "fifth" force between them as can be probed in various experiments
- These forces are long-range hence their effects can't be generalised by EFTs
- Instead, experimental direction comes from "Toy" models, almost exclusively the Yukawa case arising from tree-level scalar exchange
- To move beyond case-by-case searches a more general framework is needed

- This result is valid **regardless of the form of the hidden sector;** be it perturbative, strongly coupled, minimal, complex…
- Since $\rho > 0$ all scalar forces must be :

  1) Attractive **2) A monotonic function of distance**

The Framework

1. Consider SM states of mass *M* coupled weakly to a scalar composite operator $\mathcal{O}_{DS}$:

$$\mathcal{L}_{\text{int}} = \lambda \bar{\Psi}_{SM}\Psi_{SM}\mathcal{O}_{DS}$$

2. At $\mathcal{O}(\lambda^2)$ this generates a potential according to the Born Approximation:

$$V(\boldsymbol{r}) = -\frac{1}{4M^2}\int d^3\boldsymbol{q}\,\frac{\mathcal{M}^{\text{NR}}}{(2\pi)^3}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\ , \qquad \equiv \Delta(q)$$

where $i\mathcal{M}^{\text{NR}} = -4i\lambda^2 M^2 \langle \mathcal{O}_{DS}(x)\mathcal{O}_{DS}(y)\rangle^{\text{NR}}$

3. Assuming locality, causality and unitarity, $\Delta(q)$ can be represented in the Källén-Lehmann spectral representation as

$$\Delta(q) = 2\int_0^\infty \mu d\mu\,\frac{\rho(\mu^2)}{q^2-\mu^2+i\epsilon} \qquad \text{for a real } \rho(\mu^2) > 0$$

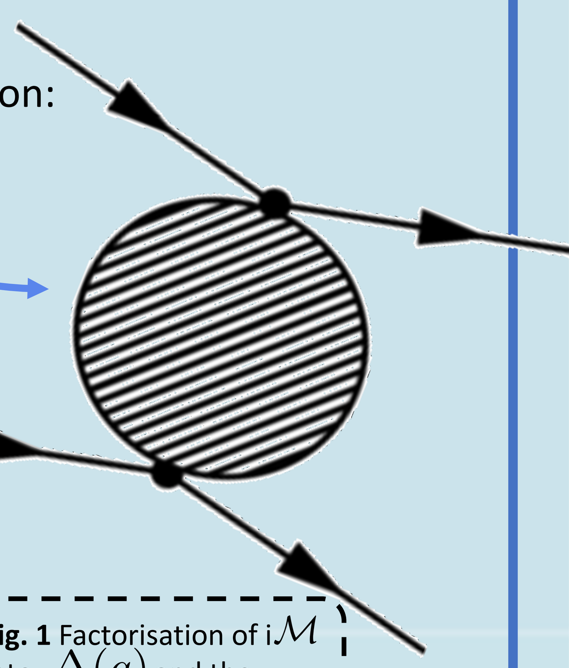


Fig. 1 Factorisation of $i\mathcal{M}$ into $\Delta(q)$ and the external SM states

4. Inserting into the Born Approximation yields **the most general form of the potential** that can be generated via scalar operator exchange within the axioms of QFT:

$$V(r) = -\frac{\lambda^2}{2\pi r}\int_0^\infty \mu d\mu\,\rho(\mu^2)e^{-\mu r}$$

Extracting the Spectral Density

- For a given interaction, ρ can be found from the imaginary part of the propagator:

$$\rho(q^2) = -\frac{1}{\pi}\text{Im}\{\Delta(q)\}\ .$$

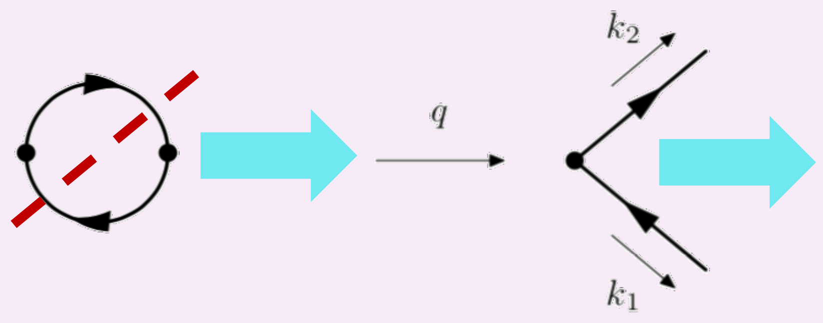
- For loop exchange, the optical theorem for forward scattering:

$$2\text{Im}\left(-\!\bullet\!-\right) = \sum_X \rhd\!\!\lhd$$

can be exploited, bypassing the need for loop integrals.

E.g. For $\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_{SM}\bar{\psi}\psi$ where $\mathcal{O}_{DS}$ is a bilinear of dark fermions, the leading order contribution to SM scattering occurs at the 1-loop level.

The imaginary part of the effective propagator (i.e .the fermion loop) can be found via the optical theorem from its tree-level cut:



$$\rho(\mu^2) \quad \frac{\mu^2\eta}{4\pi^2}\left(1-\frac{4m^2}{\mu^2}\right)^{\frac{3}{2}}\Theta(\mu^2-4m^2)$$

$$V(r) \quad -\frac{3\eta m^2}{2\Lambda^4\pi^3 r^3}K_2(2mr)$$

Beyond QFT?

- Allowing negativity into the spectral density corresponds to the violation of a QFT fundamental such as locality/unitarity/causality
- E.g., the spectral density in Fig. 3 generates a potential which displays a turning point distance, in direct contradiction with QFT constraints

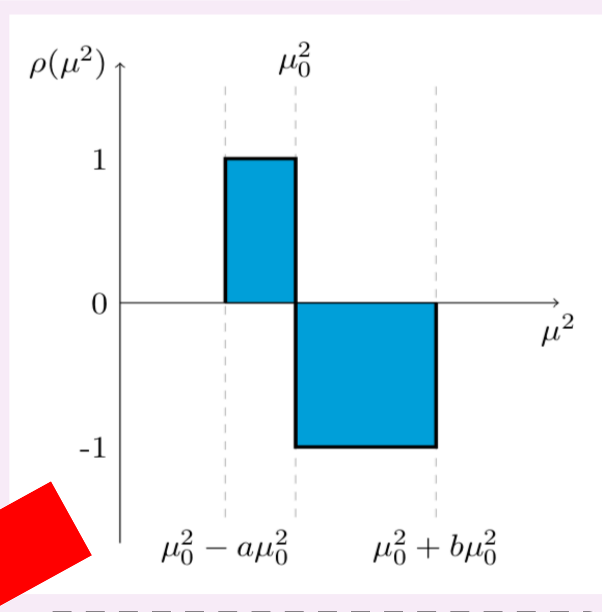


Fig. 3 An example spectral density which violates QFT

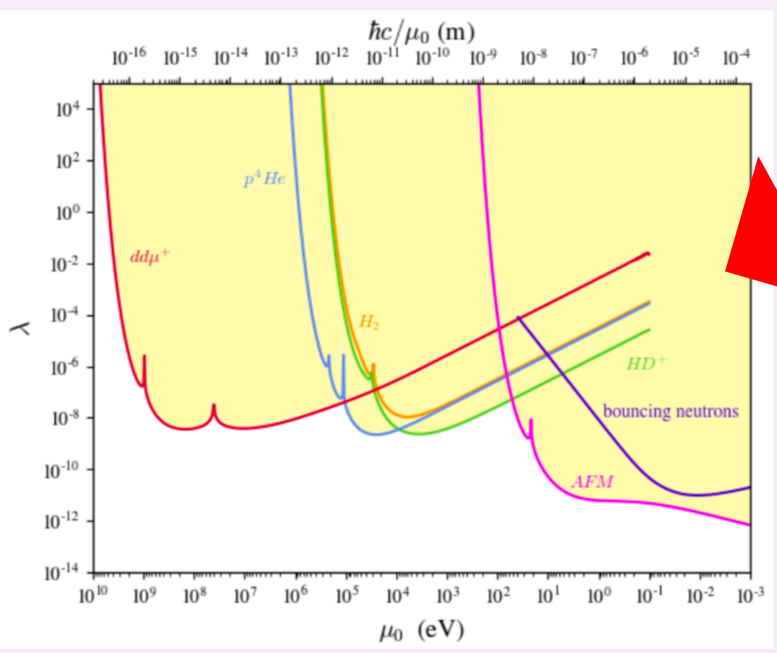


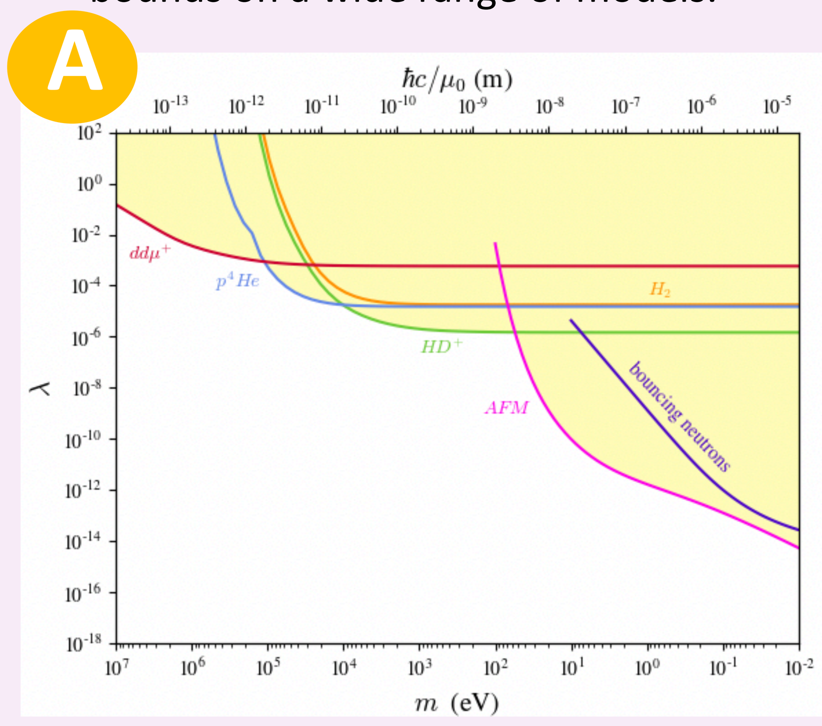
Fig. 4 Experimental bounds on the ρ of Fig. 3

- Gives us a possible probe for QFT violations in hidden sectors….
- *Caveat:* similar effects *could* arise from interference of different spin operators…

The Experimental Landscape

Any desired observable can be recast in terms of ρ making it straightforward to extract bounds on a wide range of models.

A



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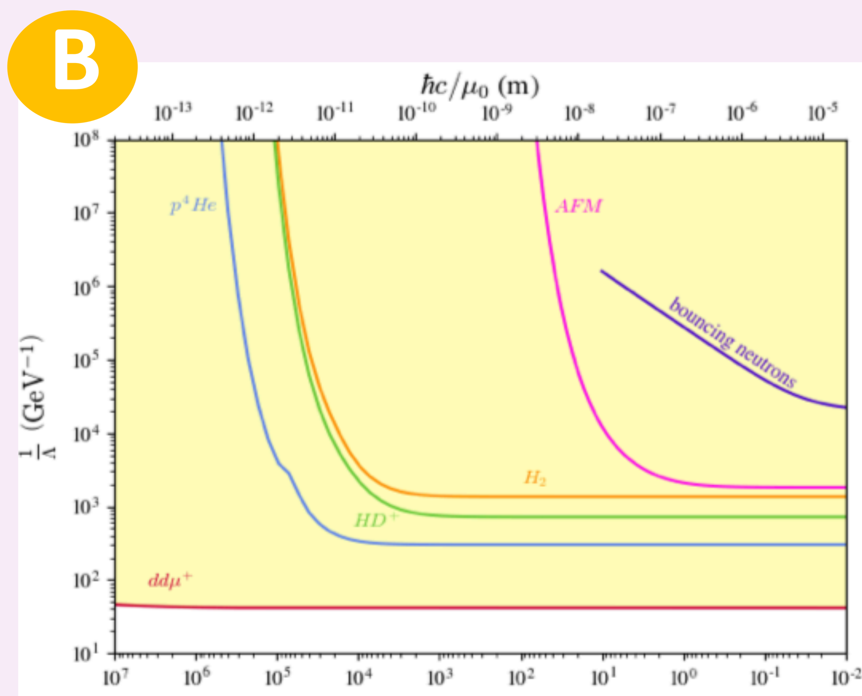
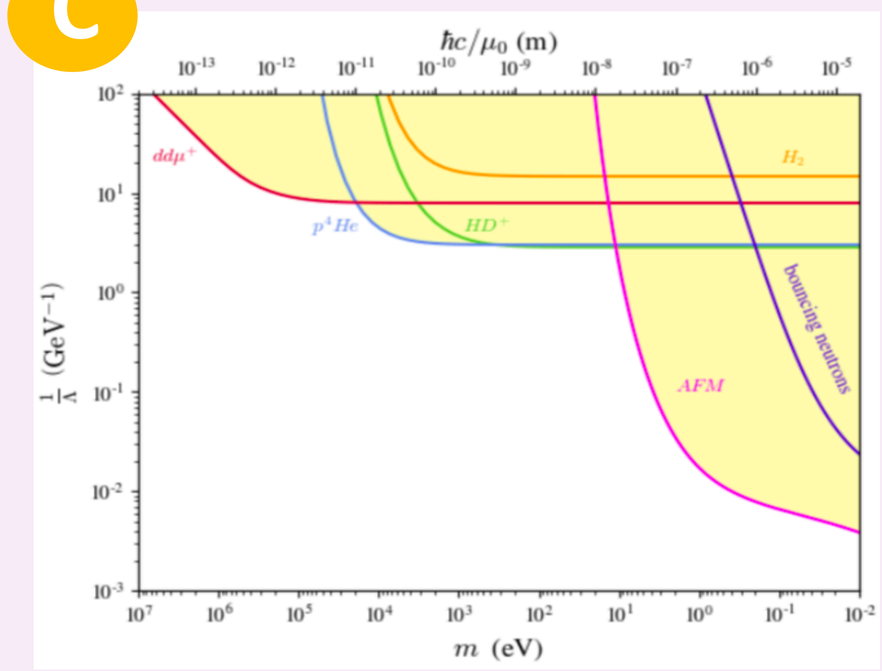


Fig. 2 A sample of experimental constraints on (A) the Yukawa interaction (B) $\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_{\text{SM}}\bar{\psi}\psi$ and (C) $\mathcal{L}_{\text{int}} = \frac{1}{\Lambda}\mathcal{O}_{\text{SM}}\phi^2$ for a real scalar ϕ

C



- Landscape of limits can vary significantly from the Yukawa case!
- Constraint hierarchy determined largely from the short distance behaviour of the potential
- As more states participate in the mediation (= higher dimensional DS operator) , bounds from short distance experiments gain importance

Conclusions

1. **All** possible scalar fifth forces can be encapsulated by a single, real, positive definite spectral function
2. Potentials from loop exchange can be obtained easily without performing loop integrals
3. Observables can be expressed in completely general terms leading to straightforward extraction of limits to any model
4. This framework provides a unique opportunity to consider more speculative scenarios such as violation of QFT fundamentals
5. The landscape of possible scalar fifth forces is much richer than the simple Yukawa scenario and well worth pursuing!