Effective Field Theory for Heavy Dark Matter of Arbitrary Spin

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ongoing work

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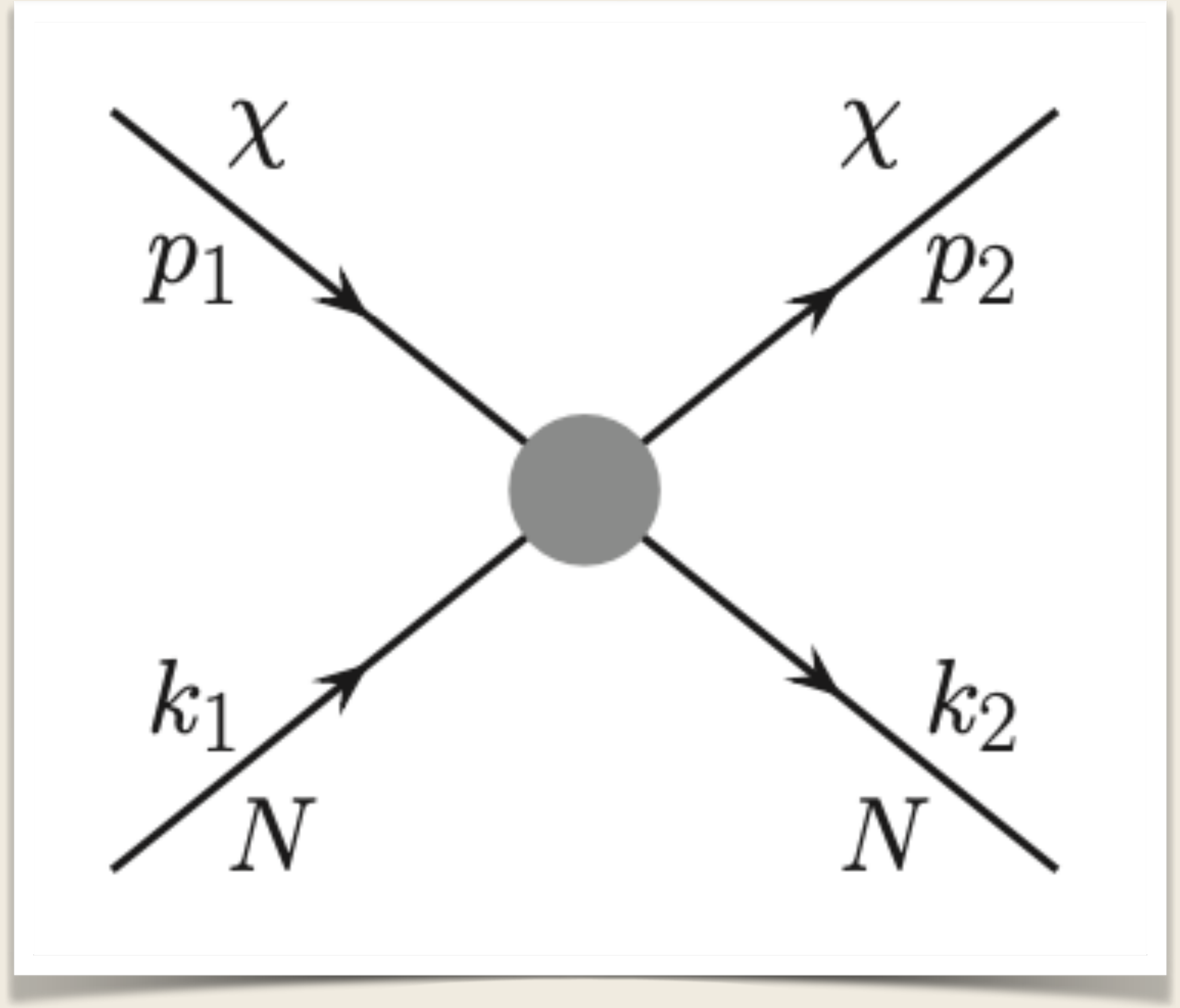
PHENO 2023, 05/08/2023

Introduction

- Goal: model independent description of direct detection experimental results.
- Consider:
    - non-relativistic DM;
    - scattering processes;
    - small momentum exchanges, i.e. $p_1 - p_2 = q \ll M$;
    - heavy mediators;
    - arbitrary spin.



- E.g. DM bound states, composite DM.

Existing approaches

EFT for relativistic DM: $\mathscr{L}_\chi = \sum_{a,d} \hat{\mathscr{C}}_a^d \mathcal{O}_a^d\,, \qquad \hat{\mathscr{C}}_a^d = \frac{\mathscr{C}_a^d}{\Lambda^{d-4}}$

- $\mathcal{O}_a^d$: $(\bar{\chi}\chi)(\bar{q}q)\,, (\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)\,, \ldots$ up to dim 7 for spin 0, 1/2, 1;
- EFT above EW scale - relate to indirect exp., LHC;
- No higher spins.

[Bishara *et al*, *JCAP* 02 (2017) 009]
[Goodman *et al*, *Phys. Rev. D* 82 (2010) 116010]

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EFT for non-relativistic DM interacting with non-relativistic nucleons: $\mathscr{L}_{NR} = \sum_{i,N} c_i^N(q^2)\mathscr{O}_i^N$

- $\mathscr{O}_i^N$: $\mathbf{1}_\chi \mathbf{1}_N \,, \vec{S}_\chi \cdot \vec{S}_N \,, \ldots,$ for any spin;
- Requires $\vec{q} \ll m_\pi$.

[Fitzpatrick *et al*, *JCAP* 02 (2013) 004]
[Jenkins, Manohar, *Phys. Lett. B* 255 (1991) 558-562]

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=> Combine the best of both: HDMEFT - NR DM for any spin with Lorentz symmetry and couplings to SM fields.

Heavy DM EFT - Little Group

- Little group is a subgroup of Lorentz transformations that is isomorphic to $SO(3)$ group of rotations and leaves time-like vector v invariant. [Heinonen *et al*, *Phys. Rev. D* 86 (2012) 094020]
- Lorentz trans. encoded in generators $\mathcal{J}^{\alpha\beta}$ which can be split into rotations $J^{\alpha\beta}$ and boosts $K^{\alpha\beta}$.

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- Build Lorentz inv. HDMEFT by
    - embedding DM fields into little group rep. and defining trans. under Lorentz group
    - requiring rotational invariance: $R^{\mu}_{\nu} v^{\nu} = v^{\mu}$ (sufficient for LO in $1/M$);
    - requiring inv. under small boosts: $\chi(x) \to \exp(i\vec{\eta} \cdot \overrightarrow{K})\, \chi(x') = e^{-iq\cdot x}(1 + \mathcal{O}(1/m_\chi^2))\, \chi_v(x')$, where $\vec{\eta} = -\vec{q}/M$ => RPI relates operators of different dimensions.

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- Define spin operator: $S_{\mu} = -\frac{1}{2}\epsilon_{\mu\alpha\beta\gamma}J^{\alpha\beta}v^{\gamma}$, e.g. spin - 1/2: $S_{\mu} = \gamma_{\mu}\gamma_5/2$.
- Choose v such that $v \to v + \frac{q}{M}$, e.g. $v^{\mu} = (1,\vec{0})$.

HDMEFT Basis and RPI

Write down HDMEFT: $\mathscr{L}_{\text{HDMET}} = \sum_{a,d} \hat{C}_a^{(d)} \mathcal{O}_a^{(d)},$

- dim 5: $\mathcal{O}_1^{(5)} = \frac{e}{4\pi^2}(\chi_v^\dagger J^{\mu\nu}\chi_v)F_{\perp\mu\nu}\,,\qquad \mathcal{O}_2^{(5)} = \frac{e}{4\pi^2}(\chi_v^\dagger J^{\mu\nu}\chi_v)\tilde{F}_{\perp\mu\nu}\,,$
- dim 6: $\mathcal{O}_{1,f}^{(6)} = (\chi_v^\dagger\chi_v)(\bar{f}\slashed{v}f)\,,\qquad \ldots$

$\ldots$

$\mathcal{O}_5^{(6)} = \frac{e}{4\pi^2}(\chi_v^\dagger S_\mu i\overleftrightarrow{\partial}_\nu\chi_v)F_\perp^{\mu\nu}\,,\qquad \ldots$

- dim 7: $\ldots$

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- dim 7: $\dots$

Reparametrization inv. e.g. : $\mathcal{O}_2^{(5)} - \frac{1}{m_\chi}\mathcal{O}_5^{(6)}$ is RPI => $\hat{C}_5^{(6)} = -\frac{1}{m_\chi}\hat{C}_2^{(5)}$.

QM Basis and Matching onto NR-nucleon interactions

- Write the basis in the QM notation:

$$
\begin{aligned}
\mathcal{O}_1^{(5)} &= \frac{e}{4\pi^2}(\chi_v^\dagger J^{\mu\nu}\chi_v)F_{\perp\mu\nu} = \rightarrow \frac{e}{2\pi^2}\vec{S}_\chi \cdot \vec{B}\,, \\
\mathcal{O}_2^{(5)} &= \frac{e}{4\pi^2}(\chi_v^\dagger J^{\mu\nu}\chi_v)F_{\perp\mu\nu} \rightarrow -\frac{e}{2\pi^2}\vec{S}_\chi \cdot \vec{E}, \\
\mathcal{O}_{1,f}^{(6)} &= (\chi_v^\dagger \chi_v)(\bar{f}\not{v}f) \rightarrow \mathbf{1}_\chi(\bar{f}\not{v}f)\,, \\
\mathcal{O}_{5,f}^{(6)} &= \frac{e}{4\pi^2}(\chi_v^\dagger S_\mu i\overleftrightarrow{\partial}_\nu \chi_v)F_\perp^{\mu\nu} \rightarrow -\frac{e}{4\pi^2}\vec{S}_\chi \cdot (\vec{p}_{12} \times \vec{B})\,.
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- Match onto NR-nucleon EFT:

$$\mathscr{L}_{NR} = \sum_{i,N} c_i^N(q^2)\mathcal{O}_i^N, \qquad \text{where } \mathcal{O}_i^N\!: \mathbf{1}_\chi \mathbf{1}_N\,, \vec{S}_\chi \cdot \vec{S}_N\,, \ldots$$

- Obtain Wilson coefficients $c_i^N(q^2)$ and compute cross-sections - direct detection experiments.

Conclusions

- Presented a way to build an EFT for heavy Dark Matter of arbitrary spin at LO in $1/M$.
- Constraints on DM bound/composite states.
- DM fields embedded in little group rep. - rotational inv.
- Lorentz invariance is present through RPI relations.
- Matching onto NR-nucleon EFT.