Lecture 17

Quantum Field Theory II: The SM + EW Theory

Felix Yu

February 3, 2021

Last time: EFTs as top-down + bottom-up tools; SM EFT

Today: EFTs in everyday use

DM EFTs & simplified models

ν-physics + seesaw physics

Recall EFTs are defined by low-energy set of dynamical fields, gauge + global symmetries, + truncation order of higher dimensional operators.

If we consider Dark Matter, then we need to introduce a new deg. of freedom to the SM that can serve as a DM candidate. The main requirements for particle dark matter are:

1. Cosmologically stable: either does not decay or lifetime is longer than the age of the universe.
2. Electrically neutral: Given DM in the galactic halo, an electric charge for DM would give photon interactions in the CMB that are excluded. Exception: microcharges.
3. Color neutral: Similar to #2, we expect a local density of DM in our solar system. Then, surface-based or underground detectors would expect to see nuclear recoils from new colored states.

4. Relic density: $\Omega h^2 \sim 0.12$ The energy budget of the universe (from CMB measurements) has been fit to $\Omega_m = 0.311 \pm 0.006$

$$\Omega_\Lambda = 0.687 \pm 0.006$$

[PDG, Cosmological Params., Table 25.1, 2020]

Ω_m includes baryonic & dark matter.

baryonic matter $\Omega_b h^2 = 0.02242 \pm 0.00014$

cold DM $\Omega_c h^2 = 0.1193 \pm 0.0009$.

$h = 0.677 \pm 0.004$

This is in the ΛCDM standard cosmological model, which is beyond the scope of these lectures.

5. Mass is 10^{-20} eV to $100 M_\odot$
$$\quad\quad\quad\quad\quad\quad\quad\quad \shortparallel$$
$$\quad\quad\quad\quad\quad\quad\quad\quad 10^{59}\text{ GeV}$$

Thermal DM is $\sim$ MeV to 100 TeV

$M_\odot = 1.989 \cdot 10^{33}$ g

$m_p = 1.67 \cdot 10^{-24}$ g

$M_\odot \sim 10^{57} m_p \sim 10^{57}$ GeV

10^{-20} eV $\sim$ fuzzy DM

10^{59} eV $\sim$ black holes (primordial)

To construct an EFT, we now also assume

- (A) DM is an SU(2) singlet.
- (B) DM is a Dirac fermion (can also do scalar or Majorana ferm)
- (C) DM is odd under $\mathbb{Z}_2$ sym, SM is even $\Rightarrow$ ensures DM stability

Write possible $\mathcal{L}$ interactions up to dim. 6:

$$\mathcal{L}_{tot} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{\substack{DM+SM\\ EFT}}$$

$$\mathcal{L}_{DM} = \bar{\chi}\, i\not{\partial}\chi - m\bar{\chi}\chi$$

$$\mathcal{L}_{\substack{DM-SM\\ EFT}} = \begin{pmatrix}\text{SM gauge}\\ \text{invariant,}\\ \text{Lorentz}\\ \text{covariant}\end{pmatrix} \otimes \begin{pmatrix}\text{DM gauge}\\ \text{invariant,}\\ \text{Lorentz}\\ \text{covariant}\end{pmatrix}$$

Note that fermion bilinears mixing SM + DM contractions can be generated by Fierz identities.

For simplicity, work in SM broken phase:

So we have only $SU(3)_c \times U(1)_{em}$ gauge symmetries.

Starting with the DM side, we have the usual 5 fermion bilinears:

$$\bar{\chi}\chi \;,\; \bar{\chi}\gamma^5\chi, \;\; \bar{\chi}\gamma^\mu\chi, \; \bar{\chi}\gamma^\mu\gamma^5\chi, \;\; \bar{\chi}\sigma^{\mu\nu}\chi.$$

These can be matched to corresponding quark bilinears, subject to overall Lorentz invariance.

$$\mathcal{L}_{\substack{DM-SM\\EFT}} = \frac{1}{\Lambda^2}\bar{q}q\,\bar{\chi}\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^5 q\,\bar{\chi}\chi + \frac{1}{\Lambda^2}\bar{q}q\,\bar{\chi}\gamma^5\chi$$
$$+ \frac{1}{\Lambda^2}\bar{q}\gamma^5 q\,\bar{\chi}\gamma^5\chi$$
$$+ \frac{1}{\Lambda^2}\bar{q}\gamma^\mu q\,\bar{\chi}\gamma_\mu\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^\mu\gamma^5\,\bar{\chi}\gamma_\mu\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^\mu q\,\bar{\chi}\gamma_\mu\gamma^5\chi$$
$$+ \frac{1}{\Lambda^2}\bar{q}\gamma^\mu\gamma^5 q\,\bar{\chi}\gamma_\mu\gamma^5\chi$$
$$+ \frac{1}{\Lambda^2}\bar{q}\sigma^{\mu\nu}q\,\bar{\chi}\sigma_{\mu\nu}\chi$$

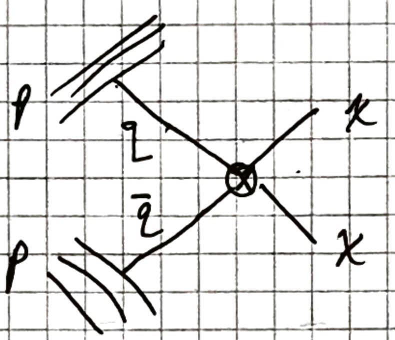
Instead of quarks, we could have also used leptons.

Note that scalar operators, such as $\bar{q}q$ + $\bar{q}\gamma^5 q$, are necessarily $SU(2)$ breaking $\Rightarrow$ $SU(2)\times U(1)_Y$ invariant operator is dim-7:

$$\frac{1}{\Lambda^3}\bar{Q}\hat{H}u_R\,\bar{\chi}\chi \quad \text{or} \quad \frac{1}{\Lambda^3}\bar{Q}Hd_R\,\bar{\chi}\chi$$

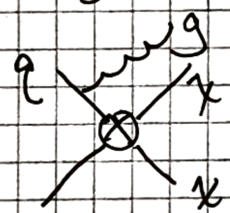
Could also use Higgs fields or Z/γ, but have to worry about gauge invariance (+ "minimal coupling").

In practice, these operators lead to collider phenomenology of dark matter production.



$$\sigma \propto |\mathcal{M}|^2 \propto \frac{1}{\Lambda^4} \cdot |C_1|^2$$

Measurements constrain strength of Wilson coefficient C_1.
In practice, cannot "see" nothing ⇒ need recoil object in final state to detect escaping χ particles.
Collider signature is monojet + $\not{E}_T$, monophoton + $\not{E}_T$, etc., where initial state radiation gives gluon, photon, $W^{+/-}$, Z, etc.



ISR jet + $\not{E}_T$.

Main challenges: ① SM Z+jet background, with $Z \to \nu\bar{\nu}$
② EFT interpretation fails if bound is too weak.