Lecture 17, February 3, 2021

Monday, February 1, 2021 11:37 AM

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

Today: EFTs in everyday use examples

① DM EFT
② Neutrino EFT + seesaw mechanism

No HW 6, but open office hours.
Bring questions or other topics to discuss.

Recall, EFTs are defined by:

① A set of low-energy / dynamical fields
② Charges / reps. under gauge + global symmetries
③ Truncation order in power counting of UV scale cutoff Λ.

Ex. $\mathcal{O}\left(\frac{1}{\Lambda^2}\right) \rightarrow$ dim.-6 operators of SM fields, known as SM EFT.

Distinguish top-down vs. bottom-up.

Ⓐ Start with UV completion, write corresponding EFT
Integrate of heavy dofs., truncate heavy mass scale. Ex. Fermi theory

Ⓑ Start with known dofs, assign symmetries (gauge + global) to the dofs., write down all operators subject to the truncation. Ex. SM EFT.

New topic: Dark Matter

We necessarily need a new field, separate from SM field content, which obeys the following 5 restrictions.

① Singlet under EM.

No electric charge.

Reason: EM interactions with CMB.

(Caveat: microcharges.)

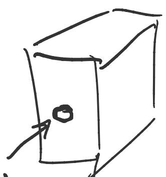
★ Small xsec with visible matter

② Singlet under color.

[Particle colliders would readily produce it ⇏ but they have kinematic limits.]

Expect DM is color-bound state.

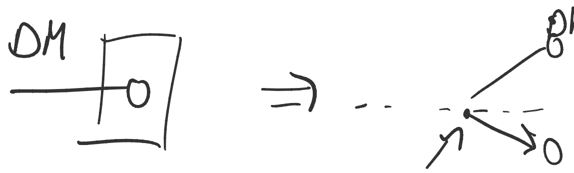
Reason: We expect solar system to be in a halo of DM. Ground-based or underground direct detection experiment would see nuclear recoils from colored DM.



target nucleus (H_2O @ Super-K vs. LXe @ Xenon 1T) waits for DM kick.

Expect dark matter density ~ $0.3\ \mathrm{GeV/cm^3}$.

Follows Maxwell-Boltzmann distrib. $\langle v \rangle \sim 220\ \mathrm{km/s}$.

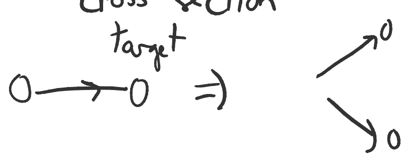


this is DM scattering cross section

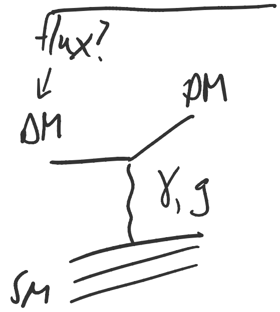
elastic scattering: mediator force.

Known force carrier: γ & $\pi^{0/\pm}$ ↪ color

Or NP mediator.



microscopically:



ν-background for direct detection

ν-background for direct detection SM —

Not currently an issue: $\sigma^{DM}_{\text{nuclear recoil}} \gtrsim 10^3\ \sigma_{\nu\text{-recoil}}$

In principle, ν-flux is known. $10^{-47}\ cm^2$ $10^{-50}\ cm^2$

Two sources $\Rightarrow$ solar neutrinos. 8 MeV. MSW ν.

Flux: # ν per s. + energy distrib. of ν.

atmospheric ν's from cosmic rays.

extra galactic ν's: not known

Can model the expected recoil distrib. from ν's + subtract.

(3.) Cosmologically stable: particle does not decay or lifetime much longer than τ_{univ}

(4). Overall relic abundance:

Today $\Omega h^2 \sim 0.12$.

Need to know ΛCDM. (See notes)

(5.) Mass range: $10^{-20}\ eV \lesssim m_{DM} \lesssim 100\ M_\odot = 10^{59}\ GeV$

fuzzy DM ↖ DM halo size

Thermal DM: is $\sim$ MeV $\lesssim m_{DM} \lesssim 100$ TeV.

↑ too warm ↑ perturbativity

(6) Must act gravitationally.

Given these "rules," we can suppose

DM is scalar or fermion (or vector.)

Assume DM is SU(2) singlet.

So, for concreteness, write EFT for DM assuming DM is fermionic SM gauge singlet: χ. (Majorana

DM is fermionic SM gauge singlet: χ. (Majorana or Dirac)

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

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

$$\mathcal{L}_{\substack{DM-SM \\ EFT}} = \begin{pmatrix} \text{SM gauge-} \\ \text{invariant} \end{pmatrix} \otimes \begin{pmatrix} \text{DM gauge-} \\ \text{invariant} \end{pmatrix} \text{ at } \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

(Typically Lorentz invariants)

For simplicity: work with broken phase SM.

$SU(3)_c \times U(1)_{em}$.

To ensure DM stability, assign $\mathbb{Z}_2$ for DM ~ +1, SM ~ 0.

Flesh out possible DM structures:

$(\bar{e}\, e)(\bar{\chi}\, \nu)$

$h(\bar{L} e)\, \tilde{h}(\bar{L}\chi)$

5 possibilities: $\bar{\chi}\chi$, $\bar{\chi}\gamma^5\chi$, $\bar{\chi}\gamma^\mu\chi$, $\bar{\chi}\sigma^{\mu\nu}\chi$, $\bar{\chi}\gamma^\mu\gamma^5\chi$

Complete EFT:

SM fermions w/ appropriate Lorentz covariance.

(& SU(3) + U(1) neutral)

$\bar{q}q$, $\bar{q}\gamma^5 q$, $\bar{q}\gamma^\mu q$, $\bar{q}\gamma^\mu\gamma^5 q$, $\bar{q}\sigma^{\mu\nu} q$

$$\mathcal{L}_{\substack{SM-DM \\ EFT}} = \frac{1}{\Lambda^2}\bar{q}q\,\bar{\chi}\chi + \frac{1}{\Lambda^2}\left(\bar{q}\gamma^5 q\,\bar{\chi}\chi + \text{swap}\right) + \frac{1}{\Lambda^2}\bar{q}\gamma^5 q\,\bar{\chi}\gamma^5\chi$$

finite set

$$+ \frac{1}{\Lambda^2}\bar{q}\gamma^\mu q\,\bar{\chi}\gamma_\mu\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^\mu\gamma^5 q\,\bar{\chi}\gamma_\mu\chi + \dots$$

finite set $+ \frac{1}{\Lambda^2}\bar{q}\gamma^{\mu}q\,\bar{\chi}\gamma_{\mu}\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^{\mu}\gamma^{5}q\,\bar{\chi}\gamma_{\mu}\chi + \dots$

$$+ \frac{1}{\Lambda^2}\bar{q}\sigma^{\mu\nu}q\,\bar{\chi}\sigma_{\mu\nu}\chi$$

Could also write leptonic bilinears.

What about other SM fields?

In broken phase, have $G^a_{\mu\nu}$, h, $A_\mu / F_{\mu\nu}$ + $W^{+/-}_\mu$ + Z^μ.

$G^a_{\mu\nu}$ does not give anything at dim-6.
↳ not gauge inv.

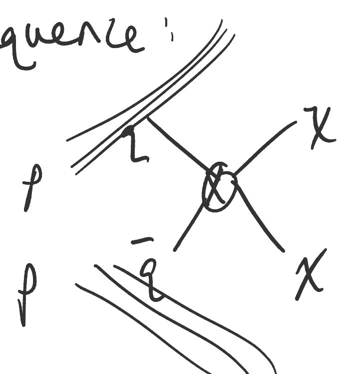
$$\frac{1}{\Lambda^4}\bar{q}\,t^a\,G^{(a)}_{\mu\nu}\,q\,\bar{\chi}\sigma_{\mu\nu}\chi$$

Similar to $W^{+/-}$ + Z, since need $SU(2)$ invariance in UV.

Can proceed to use EFT op. as effective int. at experiments to predict new phenomena & constrain/discover interactions.

Consequence:

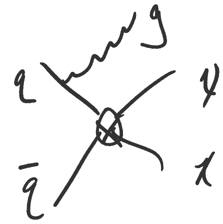
LHC scattering



$\sigma \propto |M|^2 \propto \left|\frac{C_1}{\Lambda^2}\right|^2$

$\sigma(pp \to \text{nothing})$ → not useful

Instead ∃



$\sigma(pp \to \text{jet} + \not{E}_T)$ = "monojet" search

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Can also do ISR photon ⇒ "monophoton" search

or W/Z etc. ⇒ "mono-X" search.

But exp. limits are too poor ∃ need simplified models.