Lecture 18.

QFT 3: The SM + EW Theory

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February 4, 2021

Last time: EFTs in practice

DM EFT

Today: Continue DM EFT

Simplified Models

Recall that we wrote the DM-SM EFT operators from last

$$\mathcal{L} \supset \frac{C}{\Lambda^2}\bar{q}q\,\bar{\chi}\chi + \frac{C}{\Lambda^2}\bar{q}\gamma^5 q\,\bar{\chi}\gamma^5\chi + \text{mixed}$$

$$+ \frac{C}{\Lambda^2}\bar{q}\gamma^\mu q\,\bar{\chi}\gamma_\mu\chi + \frac{C}{\Lambda^2}\bar{q}\gamma^\mu\gamma^5 q\,\bar{\chi}\gamma_\mu\gamma^5\chi + \text{mixed}$$

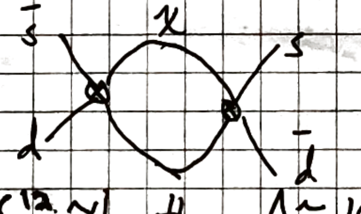
$$+ \frac{C}{\Lambda^2}\bar{q}\sigma^{\mu\nu}q\,\bar{\chi}\sigma_{\mu\nu}\chi$$

Also recall that the scalar operator necessarily corresponded to a dim-7 operator in the EW unbroken phase:

$$\frac{C}{\Lambda^2}\bar{d}d\,\bar{\chi}\chi \rightarrow \frac{C}{\Lambda^3}\bar{Q}H d_R\,\bar{\chi}\chi + \text{h.c.}$$

Aside: The flavor structure of C here is highly constrained by low-energy flavor constraints.

For example, the $K_0 - \bar{K}_0$ mixing would be affected by



$$\text{Operator} \propto \left(\frac{C^{12}}{\Lambda^2}\right)^2 \cdot \int_0^{\Lambda} d^4k \left(\frac{k}{k^2 - m_\chi^2}\right)^2$$

$$\sim \left(\frac{C^{12}}{\Lambda}\right)^2$$

For $C^{12} \sim 1$, then $\Lambda \sim 100$ TeV or higher.

The question of assigning flavor structures to new physics operators is precisely the New Physics Flavor Problem. Specifically, the C^{ij} entries have nothing to do with the (arbitrary) Yukawa matrices that give the global flavor symmetry breaking in the SM.

So the options are to decouple all new physics (send $\Lambda \to$ heavy), which also makes it impossible to see new physics directly, fine-tune the flavor structure of C^{ij} subject to ever-changing low-energy flavor measurements, or assume a flavor structure that "works."

The last option is known as the Minimal Flavor Violation ansatz, which requires that all flavor breaking structures for new physics are only built from the Y_u & Y_d matrices of the SM Yukawa interactions.

In practice, this means C^{ij} above is ~~proper~~ proportional to Y_d: Consequently, the flavor symmetry rotations to diagonalize Y_d also diagonalize C^{ij}:

$$\mathcal{L} \supset Y_d \bar{Q} H d_R + \frac{C^{ij}}{\Lambda^2} \bar{Q}^i H d_R^j \bar{\chi} \chi$$

$$\ni Y_d^{diag} \bar{Q}^m H d_R^m + \frac{C^{ij\prime}}{\Lambda^2} \bar{Q}^i_m H d^j_{R\,m} \bar{\chi} \chi$$

where $C^{ij\prime} = U_{dL}^\dagger C^{ij} U_{dR}$ & $Y_d^{diag} = U_{dL} Y_d U_{dR}$

③

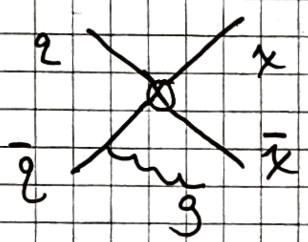
Collider Signals from DM EFT:

The $\mathcal{L}_{\substack{DM\text{-}SM \\ EFT}}$ predicts new interactions with dark matter production at colliders.

For example, consider the axial-vector operator:

$$\mathcal{L} = \frac{C_{AV}}{\Lambda^2}\, \bar{q}\, \gamma^\mu \gamma^5 q\, \bar{\chi}\, \gamma_\mu \gamma^5 \chi$$

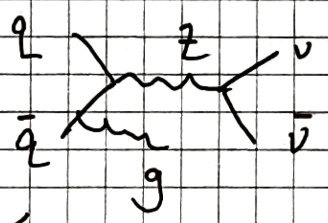
Insert this operator (flavor-blind ansatz) for pp collisions: need to radiate a gluon for ISR jet to recoil against DM pair:

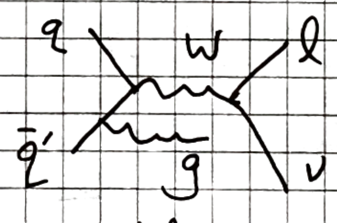


Collider signature is jet + MET.

The leading SM background is real MET from neutrinos, which are produced from $Z \to \nu\nu$ (recall this is 20% BR.), also with ISR jet.

Drell-Yan





Subleading background is $W(\to \ell\nu)$+jet, where the lepton is lost / too soft. (Recall $W \to e\nu \sim 11\%$, $\mu\nu \sim 11\%$)

The $Z \to \nu\nu$ background is an <u>irreducible</u> background.
The $W \to \ell\nu$ background is <u>reducible</u>.

Irreducible = same multiplicities of jets, leptons, MET, etc. as signal. Can only distinguish from kinematics.

Reducible = different multiplicity in at least one category.

Thus ATLAS + CMS can search for events with 1 jet + $\not{E}_T$.
Initially, though, they realized that the EFT bounds they got were very weak, meaning they could only ~~can~~ could constrain $\frac{C_{AV}}{\Lambda^2}$ at a large number.
This fails the EFT closure test, since the EFT is generally valid below Λ scales. (Example: G_F theory uses v as scale, but m_W emerges before we reach scale v!)

For example, in 1210.4491, ATLAS extracted bounds on scalar, vector, axial-vector, tensor, + gluon operators in Table 9:

m_χ	D1	D5	D8	D9	D11
1	30 (29)	687 (658)	687 (658)	1353 (1284)	347 (335)
5	30 (29)	687 (658)	687 (658)	1353 (1284)	347 (335)
10	30 (29)	687 (658)	687 (658)	1353 (1284)	347 (335)
50	30 (29)	682 (653)	666 (638)	1338 (1269)	343 (331)
100	29 (28)	681 (653)	650 (623)	1310 (1243)	334 (322)
200	27 (26)	658 (631)	595 (570)	1202 (1140)	331 (319)
400	21 (20)	571 (547)	475 (455)	943 (893)	301 (290)
700	14 (14)	416 (398)	311 (298)	629 (596)	232 (223)
1000	9 (9)	281 (269)	196 (188)	406 (384)	171 (165)
1300	6 (6)	173 (165)	110 (106)	240 (227)	118 (114)

Table 9. ATLAS 90% (95%) CL observed lower limits on the suppression scale M_* as a function of WIMP mass m_χ. All values are given in GeV and correspond to the nominal observed limit excluding theoretical uncertainties. The signal regions with the best expected limits are quoted in all cases, SR3 is used for D1, D5 and D8, SR4 for D9 and D11.

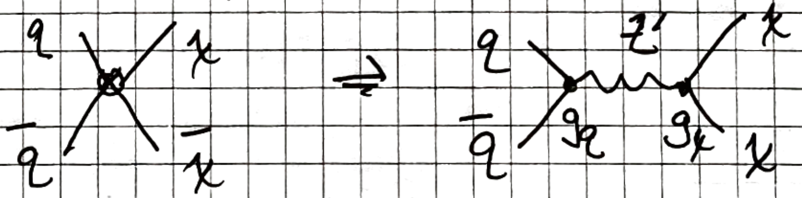
We see immediately that some $\frac{1}{M_*} = \frac{C_*}{\Lambda}$ scales extracted are much below the jet $p_T = 100$ GeV ~~scales~~ kinematics probed + this is inconsistent for $C_* = 1$, and only works for $C_* \gg 1$. But this breaks perturbativity.

Example: $M_* = 30\,\text{GeV} = \frac{\Lambda}{C}$

For $\Lambda = 1\,\text{TeV}$ to apply s.t. the EFT is valid, we need $C \sim 33$. Typically, C is the combination of $\mathcal{O}(1)$ factors of π, coupling constants + possible loop factors, in a perturbative UV completion. Hence, this M_* is difficult to take seriously as a bound, because any "normal" UV completion already introduces dynamical dofs. below the M_* scale that is already below the kinematics probed by the collider. So we expect the UV dofs. to be dynamical + relevant at this scale.

The fix for this EFT approach was the <u>simplified model</u>, which is the next step towards a UV completion of the EFT operator, aimed at re-introducing the dynamical dof. to match the operator at lowest order in the momentum expansion. Consequently, the simplified model is generally <u>not</u> UV complete.

Ex: AV operator can be embedded as an s-channel simplified model Z'.



$$\mathcal{L} = g_q Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

$$+ \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

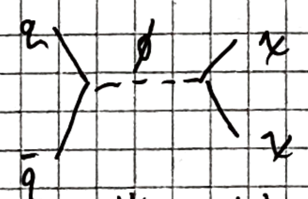
So the AV operator $\frac{C_{AV}}{\Lambda^2} \to \frac{g_q g_\chi}{m_{Z'}^2}$

Note: this is not UV complete, since the Z' mass should come from a Higgs model & the Z' couplings should come from an anomaly-free $U(1)$ gauge symmetry.

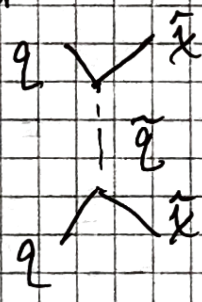
Note: Alternate t-channel simplified model needs direct $q\chi$ axial vector couplings (weird vector model).

We also see that there are separate g_q + g_χ "visible" and "invisible" couplings. The combination are responsible for the MET + jet signal, but the g_q coupling already gives a visible dijet resonance signal. The parameter space in modern studies is usually fixed as a mass-mass plot $(m_{Z'}, m_\chi)$ for fixed choices of g_q + g_χ. (See ATLAS exotics CONF-2020-048.)

Another example: scalar operator



Higgs-like boson



MSSM-like squark (Z_2 odd)

$\tilde{q}$ must be colored.