Lecture 16 

QFT 3: The SM and Electroweak Theory

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Today: EFTs, SM EFT, Matching to UV models

Recall from last time, we discussed EW oblique corrections.

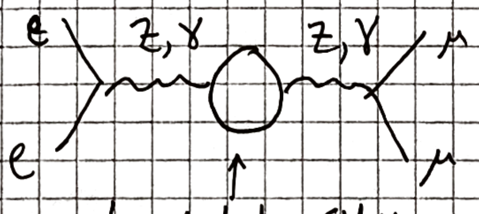
These were constructed in the experimental context of the LEP collider, which was dedicated (in Run I) to a precision study of Z production. Given that we have 4 different 2-pt. correlation fcns, $\Pi_{WW}$, $\Pi_{ZZ}$, $\Pi_{Z\gamma}$, $\Pi_{\gamma\gamma}$, we specifically want to study these form factors at $s = m_Z^2$ + $s = 0$.

$$S \equiv \frac{4c^2s^2}{\alpha_e}\left[\frac{\Pi_{ZZ}^{new}(m_Z^2) - \Pi_{ZZ}^{new}(0)}{m_Z^2} - \frac{c^2-s^2}{cs}\frac{\Pi_{Z\gamma}^{new}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}^{new}(m_Z^2)}{m_Z^2}\right]$$

$$T \equiv \frac{1}{\alpha_e}\left[\frac{\Pi_{WW}^{new}(0)}{m_W^2} - \frac{\Pi_{ZZ}^{new}(0)}{m_Z^2}\right]$$

$$U \equiv \frac{4s^2}{\alpha_e}\left[\Pi_{WW}^{new}(m_W^2) - \Pi_{WW}^{new}(0) - \frac{c}{s}\frac{\Pi_{Z\gamma}^{new}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}^{new}(m_Z^2)}{m_Z^2}\right] - S$$

In practice, these show up via 1-loop graphs like:




loop includes SM + possible heavy new physics

Since we now have LHC, with a pp collider, control over a specific $\sqrt{s}$ is not allowed & instead we are motivated to understand effects on the entire $Q^2$ range of the form factors. So the current focus experimentally ~~is~~ are differential distributions for gauge boson interactions, which probe the 2-pt. correlation fcns. over all $Q^2$.
The natural language for studying differential distributions is EFTs.

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Basics of EFTs.

Any EFT is defined by:

1. A set of dynamical (light) fields
2. Charges + reps. of the fields under gauge and/or global symmetries
3. All possible $\mathcal{L}$ operators up to a given power counting in $\frac{1}{\Lambda}$, usually $\mathcal{L}_6 \propto \frac{1}{\Lambda^2}$.

The prototypical example of an EFT is the Fermi interaction.

Fields are $e, \mu, \nu_e, \nu_\mu$ + include usual QED charges.
The dim-6 operator is

$$\mathcal{L}_F = \bar{e}\, \gamma^\mu P_L\, \nu_e\ \bar{\nu}_\mu\, \gamma^\mu P_L\, \mu$$

But, the complete set of possible dim-6 operators is much bigger.

[Built from fermion bilinears]

For example:

scalar operators: $\bar{e} e \, \bar{\mu} \mu$ , $\bar{\nu}_e e \, \bar{\mu} \nu_\mu$

pseudoscalar ops: $\bar{e} \gamma^5 e \, \bar{\mu} \gamma^5 \mu$, $\bar{\nu}_e \gamma^5 \nu_\mu \, \bar{e} \gamma^5 \mu$
+mixed

vector / axial-vector: Replace $P_L$ by $P_R$ in fermi interaction
+ tensor : $\bar{e} \sigma^{\mu\nu} e \, \bar{\nu} \sigma_{\mu\nu} \nu$

Since $\nu_e$ + $\nu_\mu$ share quantum numbers, ~~we~~ & since $e$ + $\mu$ share quantum numbers, we actually have 2 flavors of each $\nu$ & $e$ $\Rightarrow$ should allow both flavor-diagonal & flavor-violating couplings.

This illustrates the distinction between top-down + bottom-up approaches to EFT construction.

(A) In a top-down approach, we assume the UV model to start with and then construct the EFT description by integrating out explicit heavy degrees of freedom in the UV model. This is the approach for getting the $G_F$ interaction in the SM & why the additional (scalar, etc.) operators above are not included.

(B) In a bottom-up approach, the UV physics is not assumed + therefore, all possible operators ~~&~~ built from low energy dofs. should be included. The instinct to discard some set of allowed operators then reflects a prejudice against possible UV completions.

So, we can distinguish a top-down EFT where the SM is the UV theory & we integrate out the W, Z, Higgs boson & top quark. This generates only a subset of possible operators involving the remaining light quarks, leptons, gluon, & photon.

In contrast, the goal of EFT studies at the LHC are focused on considering the SM as the light dofs. for some possible UV completion. Then, we are going bottom-up, & should write (for example) all possible dim-6 ops.

A complete taxonomy was done in 1008.4884 by Grzadkowski, Iskrzynski, Misiak & Rosiek.

There are 59 operators ($N_f = 1$) that conserve Baryon number.

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The downside of a bottom-up approach is that the superset of UV completions for all ops. usually makes no sense.

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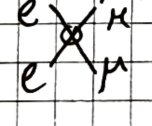
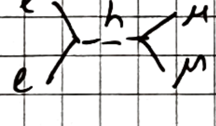
In general, it is straightforward to find (tree-level) UV completion of some dim-6 operator. We typically need to split the op. into two pieces & put a renormalizable vtx. on each side with a new ~~heavy~~ heavy particle.

Ex. $\bar{e} e \bar{\mu} \mu \Rightarrow h \bar{e} e + h \bar{\mu} \mu$



Finally, EFTs have non-renormalizable (higher-dim) ops., but they are generally <u>renormalizable</u>. In particular, their renormalizability is assured when constructing a UV completion, renormalizing the UV completion, and then matching to the effective theory again.

In practice, this imposes an explicit cutoff scale for UV divergences in the EFT calculations, which corresponds to EFTs having a fixed & finite regime of validity.

Next time:

DM EFT + simplified models

Neutrino physics + Majorana operator