Effective Field Theories and Neutrinos

Tyler Corbett

Niels Bohr Institute

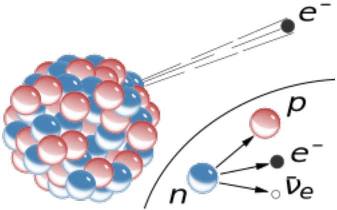
Largely inspired by Y. Cai, J. Herrero Garcia, M. Schmidt, A. Vicente, R. Volkas, arXiv:1706.08524

Outline

1. Basics of EFTs
2. Neutrino masses and EFTs
3. QFTs as a tower of EFTs
4. References

Fermi-theory I: Bottom up, neutron decay

Prior to the SM we didn't have a 'fundamental' explanation for β/neutron decay.



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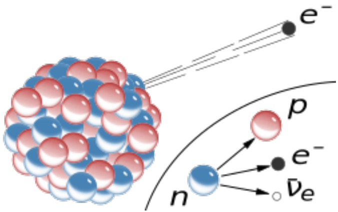

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- let's take the field content and symmetries of QED
- form operator that could explain neutron decay

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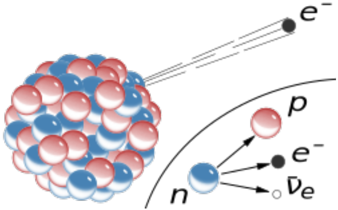

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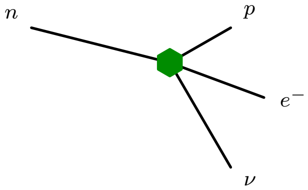

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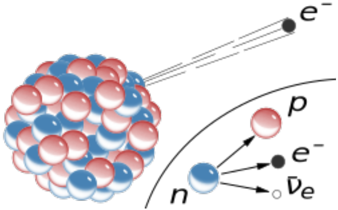

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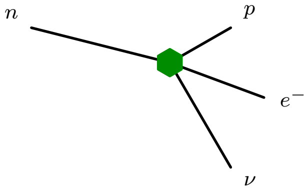
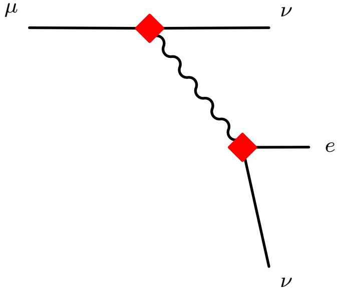
$$[G_F] = \frac{1}{M^2}$$



In the SM

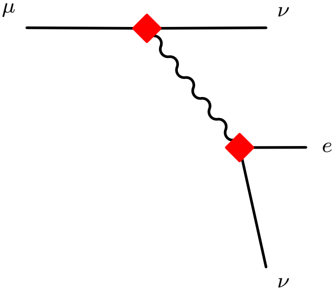


$$\mathcal{L} = \frac{g_W}{\sqrt{2}} \bar{\nu}_\mu \gamma^\mu P_L \mu W_\mu + \frac{g_W}{\sqrt{2}} \bar{e} \gamma^\mu P_L \nu_e W_\mu$$

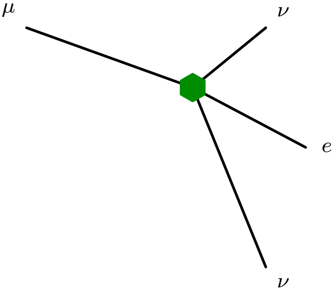
$$\mathcal{M} \sim \frac{g_W^2}{2} (\bar{\nu}_\mu \gamma^\mu P_L \mu) \frac{g_{\mu\nu}}{k^2 - M_W^2} (\bar{e} \gamma^\nu P_L \nu_e)$$

Fermi-theory II: top down, muon decay

In the SM



In the Fermi theory



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$$\frac{1}{M_W^2} (\bar{\psi} \gamma^\mu P_L \psi)^2$$

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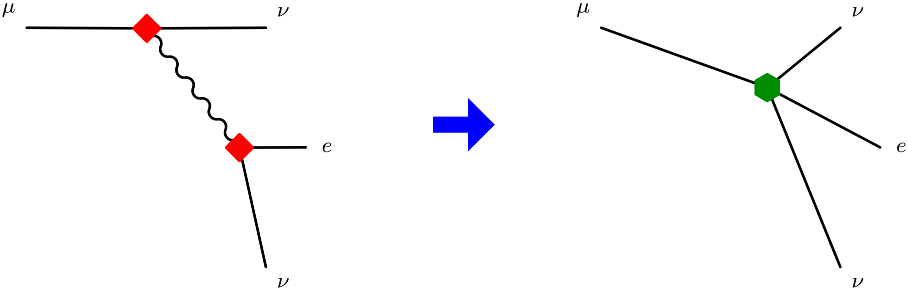

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$$\frac{1}{M_W^2} (\bar{\psi} \gamma^\mu P_L \psi)^2 \qquad \frac{1}{M_W^4} \partial^2 (\bar{\psi} \gamma^\mu P_L \psi)^2$$

$$\mathcal{M} \sim -\frac{g_{\rm W}^2}{2 M_W^2} (\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e} \gamma^\mu P_L \nu_e) - \frac{g_{\rm W}^2 k^2}{2 M_W^4} (\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e} \gamma^\mu P_L \nu_e) + \cdots$$

EFTs

$\Lambda_{\rm NP}$

The major underlying assumption of any EFT

$\Lambda_{\rm NP} \gg E$ of the scale of experiments/measurements

E–scale of experiments

EFTs

Λ_{NP}

Bottom up EFTs:

- example: Fermi theory
- Start w/ infrared (IR)–model in mind (QED, SM)
- using symmetries of model put together ops, $Q^{d>4}$
- truncate EFT at some $\mathcal{O}(1/\Lambda)$
- constrain Q in experiment & infer properties of NP at Λ
- Qs are unrelated $\rightarrow$ model independent
- Qs are only in terms of IR degrees of freedom

E–scale of experiments

Λ_{NP}

Top down EFTs:

- example: SM $\rightarrow$ Fermi theory
- Start w/ ultraviolet (UV)–model in mind (Seesaw, SUSY, etc)
- "integrate out" heavy degrees of freedom at UV scale
- model dependent relations between ops, $Q_i^{d>4}$
- Q_i are only in terms of IR degrees of freedom

E–scale of experiments

SMEFT

In studying NP at $\Lambda_{\rm NP} \gg v$, we (mostly) employ the Standard Model EFT

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \qquad \mathcal{L}_d = \sum_i c_i Q_i$$

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The leading operator:
$$\mathcal{L}_5 = c_{\alpha\beta}(\bar{L}^c_\alpha \tilde{H}^\dagger)(\tilde{H}^\dagger L_\beta) \sim v^2 \bar{\nu}^c_\alpha \nu_\beta$$
$$\Rightarrow m_\nu \sim v^2/\Lambda$$

The Weinberg operator

S. Weinberg, Phys.Rev.Lett. 43 (1979) 1566-1570

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below EWSB this gives:

$$H \to \begin{bmatrix} \phi^+ \\ \frac{v+h+\phi^0}{\sqrt{2}} \end{bmatrix} \qquad L_\alpha \to \begin{bmatrix} \nu_{L,\alpha} \\ e_{L,\alpha} \end{bmatrix}$$

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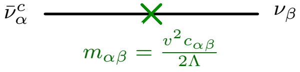

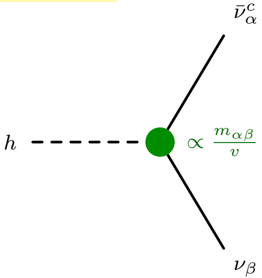

Top down neutrino masses

Previously:

- Bottom up: Fermi Theory $\frac{1}{M_W^2}(\bar{\psi}\psi)(\bar{\psi}\psi) \Rightarrow W$-boson & SM
- Top down: W-boson $\Rightarrow$ Fermi theory $\frac{1}{M_W^2}(\bar{\psi}\psi)(\bar{\psi}\psi)$

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Now:

- Bottom up: Weinberg Operator $\frac{1}{\Lambda}(\bar{L}^c H)(HL)$
- Top down: ???

Type-I seesaw

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Let's try Type-I seesaw (heavy majorana ν_R):

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R^c(\not{\partial} - M)\nu_R + y_{\alpha\beta}\tilde{H}^\dagger L_\alpha \nu_{R,\beta} + h.c.$$

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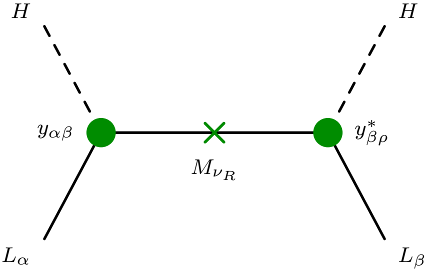

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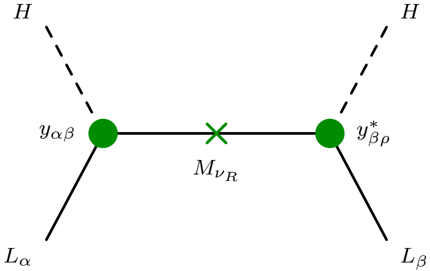

$$\mathcal{M} = y_{\alpha\beta} y^*_{\beta\rho} \frac{\bar{\psi}(\not{p} + M)\psi}{p^2 - M^2} \sim \frac{y_{\alpha\beta} y^*_{\beta\rho}}{M} \bar{\psi}\psi + \mathcal{O}\left(\frac{p}{M^2}\right)$$

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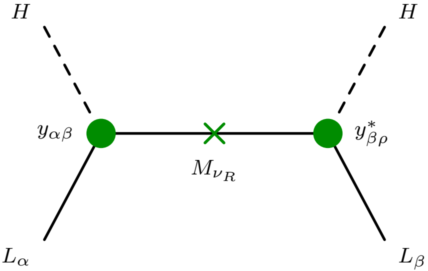

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This corresponds to:

$$\mathcal{L}_5 = \frac{c_{\alpha\rho}}{\Lambda} (\bar{L}^c_\alpha \tilde{H})(\tilde{H}^\dagger L_\beta) \qquad c_{\alpha\rho} \sim y_{\alpha\beta} y^*_{\beta\rho}, \quad \Lambda = M_{\nu_R}$$

Type II Seesaw

What about the other seesaws?
Type-II seesaw (heavy triplet scalar Δ):

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\Delta}^a(D^2 - M^2)\Delta^a + gH^\dagger\sigma^a\tilde{H}\Delta^a + y_{\alpha\beta}\bar{L}^c_\alpha\sigma_2\tau^a L_\beta\Delta^a$$

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g has units of mass

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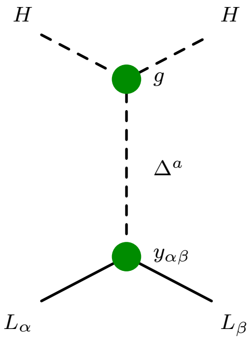

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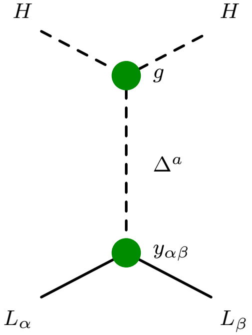

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Again we obtain the Weinberg operator:

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Type-III seesaw (heavy triplet fermion Σ):

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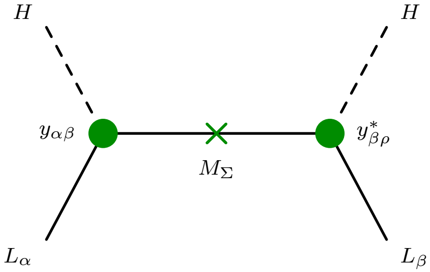

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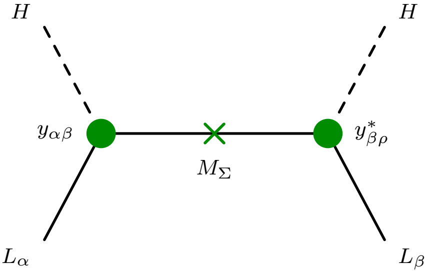

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Model Independence

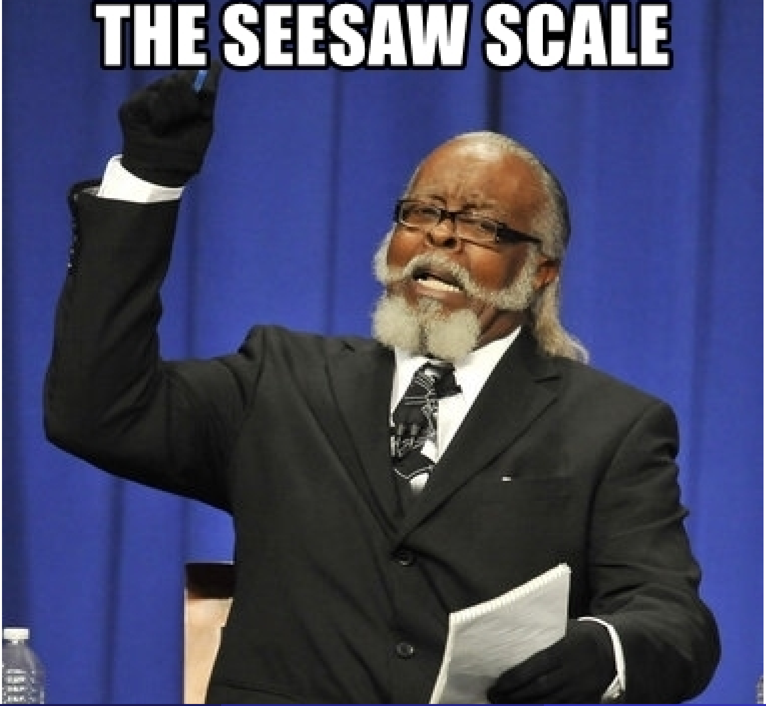
3 different models of ν mass generation give the same (leading) operator.

Implicit assumptions:

- New particles were much heavier than SM particle content:

$$m_\nu \sim .05 \text{ eV} \sim \frac{v^2}{\Lambda_{\text{seesaw}}} \quad \Rightarrow \quad \Lambda \sim \frac{(246 \text{ GeV})^2}{.05 \cdot 10^{-9} \text{ GeV}} \sim 10^{15} \text{ GeV}$$

- We assumed SM gauge symmetries and fields (well justified, except maybe Higgs doublet)
- We assumed the scale of generation of ν masses was above EWSB, i.e. used SM doublet fields like L and H instead of components ν and h


THE SEESAW SCALE

What if I want to see the particles responsible for ν masses in my lifetime?

Kumerički et al. arXiv:1204.6599

Fermionic Quintuplet, $(1,5,0)$: Σ^A
Scalar Quadruplet, $(1,4,-1)$: Φ^I

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\Sigma}^A(\not{D} - M)\Sigma^A - (\Phi^I)^\dagger(D^2 - M^2)\Phi^I - (y_{\alpha\beta}\bar{L}_\alpha\Phi\Sigma_\beta + h.c.) + \lambda\Phi H^3 + \cdots$$

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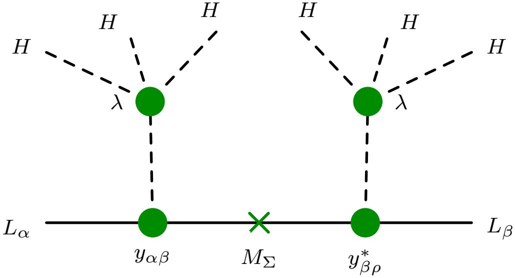

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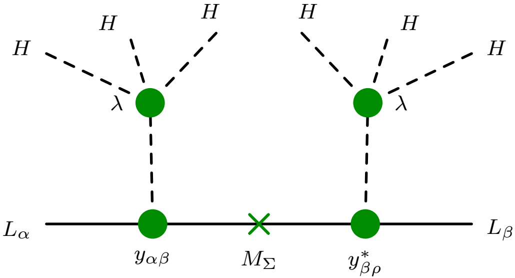

$$\mathcal{M} \sim y_{\alpha\beta} y^*_{\beta\rho} \lambda^2 \frac{\bar{\psi}(\not{p} + M)\psi}{(p^2 - M^2)^3} \rightarrow \frac{\lambda^2 y_{\alpha\beta} y^*_{\beta\rho}}{M^5} \bar{\psi}\psi + \mathcal{O}\left(\frac{p^2}{M^7}\right)$$

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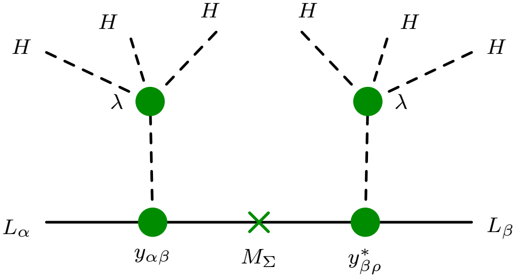

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A new form of the Weinberg operator is the leading contribution:

$$\mathcal{L}_9 = \frac{c_{\alpha\rho}}{\Lambda^5} (\bar{L}^c_\alpha \tilde{H})(\tilde{H}^\dagger L_\beta)(H^\dagger H)^2 = \frac{\mathcal{L}_5 (H^\dagger H)^2}{\Lambda^4} \qquad c_{\alpha\rho} \sim y_{\alpha\beta} y^*_{\beta\rho} \lambda^2, \qquad \Lambda = M_\Sigma = M_\Phi$$

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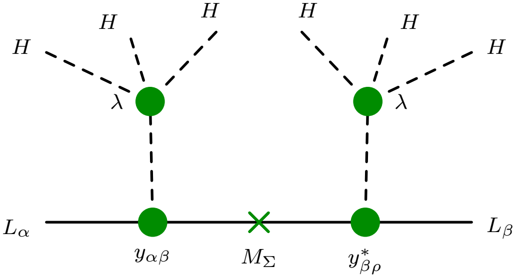

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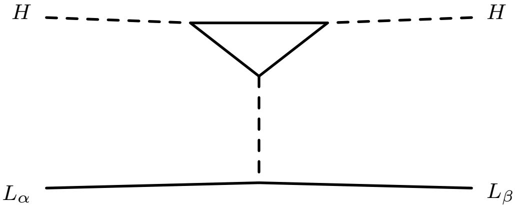
$$m_\nu \sim .05 \text{ eV} \sim \frac{v^6}{\Lambda^5} \qquad \Rightarrow \qquad \Lambda \sim \sqrt[5]{\frac{(246 \text{ GeV})^6}{.05 \cdot 10^{-9} \text{ GeV}}} \sim 85 \text{ TeV}$$

What if I want to see the particles responsible for ν masses in my lifetime? II

Could induce the Weinberg operator via loops:



$$m_\nu \sim .05 \text{ eV} \sim \frac{1}{16\pi^2}\frac{v^2}{\Lambda} \qquad \Rightarrow \qquad \Lambda \sim \frac{(246 \text{ GeV})^2}{16\pi^2(.05 \cdot 10^{-9} \text{ GeV})} \sim 10^{12}\text{GeV}$$

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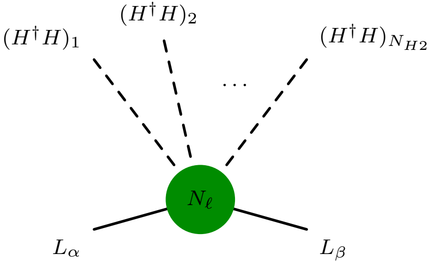
Or a combination of mass suppressions and loops:



$$m_\nu \sim .05 \text{ eV} \sim \left(\frac{1}{16\pi^2}\right)^{N_\ell} \left(\frac{v}{\Lambda}\right)^{2N_{H2}-1} v$$

N_ℓ	N_{H2}	Λ
0	1	10^{15} GeV
0	2	10^{6} GeV
0	3	85 TeV
0	4	16 TeV
0	5	6 TeV
1	1	10^{12} GeV
1	2	700 TeV
1	3	31 TeV
1	4	8 TeV
2	1	10^{10} GeV
2	2	140 TeV
2	3	11 TeV
3	1	10^{8} GeV
3	2	26 TeV
4	1	10^{6} GeV
4	2	5 TeV

Summary

Discussed:

- EFTs are model independent (mostly)
  3 tree level models with different field content/couplings $\to$ 1 operator
- Simpler low E dynamics
  can study the SM + one or some operators instead of many UV models
- "opening up" the operators
  can motivate UV models by an operator you want to generate in the IR
  If we want TeV scale neutrino mass generation, e.g. $N_\ell = 1,\ N_{H2} = 4$

Important, but not discussed:

- EFTs allow us to deal with non-perturbative physics
  e.g. if strong dynamics were to generate ν masses
  e.g. the theory of π, κ, p, n (chiral perturbation theory) is an EFT
- can adapt by including RH neutrinos in ops for Dirac neutrinos
- modern view of QFTs is a tower of EFTs

Beyond the Standard Model

$$\mathcal{L}_{\rm BSM} = \mathcal{L}(\Phi_{\rm NP}, H, Q, L, u_R, d_R, e_R, W^I, B, G^A)$$

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Standard Model + SMEFT

$$\mathcal{L}_{\text{SM}} + \sum_n \frac{1}{\Lambda^n}\mathcal{L}^{(n+4)} = \mathcal{L}(H, Q, L, u_R, d_R, e_R, W^I, B, G^A)$$

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LEFT

$$\mathcal{L}_{QED} + \mathcal{L}_{QCD} + \sum_n \frac{1}{v^n}\mathcal{L}^{(n+4)} = \mathcal{L}(2\times u, 3\times d, 3\times e, \gamma, G^A)$$

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QED+

$$\mathcal{L}_{QED} + \sum_n \frac{1}{\Lambda_{QCD}^n} \mathcal{L}^{(n+4)} = \mathcal{L}(\gamma, e^{\pm}, \pi^{\pm,0}, p, n)$$

A tower of EFTs

Top down ⇒ correlations between operators in the IR theory,
Above EWSB:

$$\mathcal{L} = i\bar{L}\not{D}L = i\bar{L}\gamma^\mu(\partial_\mu - \frac{i}{2}g_1 B_\mu + ig_2\tau^A W_\mu^A)L$$

Below EWSB:

$$\mathcal{L} \to -\frac{1}{2}Z_\mu\left[(g_1 s_W + g_2 c_W)\bar{\nu}_L\gamma^\mu\nu_L + (g_1 s_W - g_2 c_W)\bar{e}_L\gamma^\mu e_L\right]$$

Testing the SM

An example interaction, Bustamante et al. arXiv:2001.04994

$$\mathcal{L} \sim g_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$$

UV completing this theory requires:

- rewrite interaction in terms of $L_\alpha = \{\nu_{L,\alpha}, \ell_\alpha^-\}$
  $\rightarrow$ implies charged interactions with $\phi \rightarrow$ more stringent constraints
- or assume the SM is 'wrong'

So searches like these:

- look for new physics
- but also test the SM (via implied relations between interactions)

Some references

1. On Effective Field Theories, Schwartz QFT book, Ch22
2. Formalism of Integrating out particles, arXiv:1412.1837
3. On the Weinberg operator and UV completions, arXiv:1706.08524 (used in this talk)
4. On the SMEFT, arXiv:1706.08945
5. An alternative to the SMEFT, the HEFT, arXiv:1311.1823
6. Integrating out the W,Z,t,H from SMEFT to LEFT, arXiv:1908.05295

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