Testing SMEFT with $b \to c\tau^-\bar{\nu}$ Decays

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SMEFT vs. HEFT

- The SM is undoubtedly correct,
- But it is not complete (DM, baryon asymmetry of universe, neutrino masses, ...)
- $\Longrightarrow$ there must exist physics beyond the SM.
- No new particles seen at LHC $\Longrightarrow$ the NP must be heavy.
- When this NP is integrated out (at the scale of $O(\mathrm{TeV})$), get an EFT that obeys the SM symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The SM is the leading part of this EFT.

Question: is the SM symmetry realized linearly (SMEFT) or nonlinearly (e.g., HEFT)? Since the discovery of the Higgs boson, the SMEFT is the default assumption, but HEFT is still possible.

This question can only be answered experimentally.

Power Counting

Consider a non-standard $Z\bar{u}_R u_R$ coupling: $g_z\, Z_\mu(\bar{u}\gamma^\mu P_R u)$. Within HEFT, it is mass-dimension 4, so $g_z \sim O(1)$. But within SMEFT, it arises at dimension-6 from $\Lambda_h^{-2}(H^\dagger D_\mu H)(\bar{u}\gamma^\mu P_R u)$. Thus, $g_z \sim v^2/\Lambda_h^2$.

$\exists$ other dimension-6 operators that do not involve the Higgs field (e.g., 4-fermion operators). Their coefficients $\sim 1/\Lambda^2$, where Λ is the scale of NP, $\gtrsim O(\mathrm{TeV})$.

SMEFT assumption: $\Lambda_h = \Lambda \Longrightarrow$ within SMEFT, g_z is considerably smaller than its HEFT value.

How to test this assumption? (i) identify operators whose power counting is different in SMEFT and HEFT, (ii) find ways of measuring these operators. If it is found that the coefficient of such an operator is larger than that predicted by SMEFT $\Longrightarrow$ non-SMEFT NP.

LEFT

We want to test SMEFT with B decays, whose scale is $O(m_b)$. Here, the EFT is the LEFT (also WET), obtained by also integrating out the heavier SM particles ($W^{\pm}$, Z^0, H, t). (This is like the Fermi theory.)

In 1709.04486, Jenkins, Manohar and Stoffer (JMS) present a complete and non-redundant basis of LEFT operators up to dimension 6. We focus on those operators that conserve lepton and baryon number.

Note: all dimension-6 LEFT operators must respect $U(1)_{em}$. Most of them are also invariant under $SU(2)_L \times U(1)_Y$, and can be generated from dimension-6 SMEFT operators. However, a handful of dimension-6 LEFT operators are not invariant under $SU(2)_L \times U(1)_Y \Longrightarrow$ they are not generated by dimension-6 SMEFT operators. These "non-SMEFT operators" are the ones that interest us.

Non-SMEFT Operators

We have identified a number of non-SMEFT 4-fermion operators, and found the dimension-8 SMEFT operators that generate them. But we also have to find ways of measuring them, which is non-trivial. With this in mind, I focus on one of these, the non-SMEFT CC semileptonic operator

$$\mathcal{O}_{\nu edu}^{V,LR} \equiv (\overline{\nu}_{Lp}\gamma^{\mu} e_{Lr})(\overline{d}_{Rs}\gamma_{\mu} u_{Rt}) + \mathrm{h.c.}$$

Consider the decay $b \to c\tau^-\bar{\nu}$. Assuming only LH neutrinos, $\exists$ five four-fermion $b \to c\tau^-\bar{\nu}$ operators:

$$O_V^{LL,LR} \equiv (\bar{\tau}\gamma^{\mu} P_L \nu)(\bar{c}\gamma_{\mu} P_{L,R} b) \quad , \qquad O_S^{LL,LR} \equiv (\bar{\tau} P_L \nu)(\bar{c} P_{L,R} b) \ ,$$
$$O_T \equiv (\bar{\tau}\sigma^{\mu\nu} P_L \nu)(\bar{c}\sigma_{\mu\nu} P_L b) \ .$$

But note: O_V^{LR} is the above non-SMEFT operator; its coefficient is suppressed by v^2/Λ^4 in SMEFT. For this reason, it is usually excluded when looking for NP in $b \to c\tau^-\bar{\nu}$.

We redid the fit, including O_V^{LR}. We found that the preferred NP solution is still O_V^{LL}, but that $O_V^{LR} = O(1)$ is still allowed. Such a value is allowed within HEFT, but not SMEFT.

Note that it is not always true that large non-SMEFT operators are still allowed. Two other such operators are

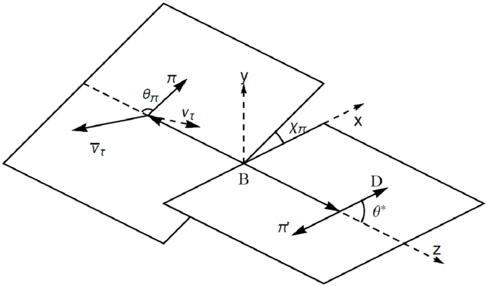
$$\mathcal{O}_{ed}^{S,RR} \equiv (\overline{e}_{Lp} e_{Rr})(\overline{d}_{Ls} d_{Rt}) \quad , \qquad \mathcal{O}_{ed}^{T,RR} \equiv (\overline{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\overline{d}_{Ls} \sigma_{\mu\nu} d_{Rt}) \ .$$

These both contribute to $b \to s\mu^+\mu^-$; their presence leads to large enhancements of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \Longrightarrow$ their coefficients are constrained to be $\leq O(10^{-3})$, consistent with SMEFT.

Measuring O_V^{LR}

In fact, O_V^{LR} *can* be measured. Consider $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$. There are four NP operators that contribute: O_V^{LL}, O_V^{LR}, $O_{LP} \equiv O_S^{LR} - O_S^{LL}$, $O_T \Longrightarrow$ 7 NP parameters (4 magnitudes, 3 relative phases).

In 2005.03032, it is proposed to measure the angular distribution in $\bar{B} \to D^*(\to D\pi')\,\tau^-(\to \pi^- \nu_\tau)\bar{\nu}_\tau$:



(i) q^2 (momentum^2 of $\tau^- \bar{\nu}_\tau$ pair) measurable, (ii) $D^* \to D\pi'$: θ^* measurable, (iii) $\tau^- \to \pi^- \nu_\tau$: E_π, θ_π, χ_π measurable.

Differential decay rate is function of q^2, E_π and 3 angles, θ^*, θ_π, χ_π. The data is separated into q^2-E_π bins, an angular analysis is performed in each bin.

Angular distribution can be written as

$$\sum_{i=1}^{9} f_i^R(q^2, E_\pi)\Omega_i^R(\theta^*, \theta_\pi, \chi_\pi) + \sum_{i=1}^{3} f_i^I(q^2, E_\pi)\Omega_i^I(\theta^*, \theta_\pi, \chi_\pi) \ .$$

The 9 $f_i^R \Omega_i^R$ terms are CP-conserving and are present in the SM. The 3 $f_i^I \Omega_i^I$ terms are CP-violating.

Point: $\exists$ 12 observables (angular functions) in each q^2-E_π bin $\Longrightarrow$ all 7 NP parameters can be extracted. If the value of $|O_V^{LR}|$ is found to be larger than that predicted by SMEFT $\Longrightarrow$ jackpot! Not just NP, but new, non-SMEFT NP.

Conclusions

It is generally thought that the SM is the leading part of an EFT obtained when the NP is integrated out. Standard idea: SMEFT is the EFT. Point: this is an *assumption*, must be determined experimentally.

One difference between HEFT and SMEFT is power counting: the coefficients of certain low-energy operators are predicted to be considerably smaller in SMEFT than in HEFT. Idea: find such an operator, measure its coefficient. If the value is found to be larger than that predicted by SMEFT $\Longrightarrow$ non-SMEFT NP!

At present, $\exists$ anomalies in $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays. One of the 5 possible NP operators – O_V^{LR} – is such a "non-SMEFT operator." It is possible to extract the coefficients of all the NP operators from the measurement of the angular distribution in $\bar{B} \to D^*(\to D\pi')\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$. If the coefficient of O_V^{LR} is found to be larger than the SMEFT prediction $\Longrightarrow$ non-SMEFT NP.