The B Anomalies and non-SMFT New Physics

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The modern viewpoint is that the Standard Model is the leading part of an effective field theory that obeys the symmetry \( SU(3)_C \times SU(2)_L \times U(1)_Y \). Since the discovery of the Higgs boson, it is generally assumed that this symmetry is realized linearly (SMEFT), but a nonlinear realization (e.g., HEFT) is still possible. The two differ in their predictions for the size of certain low-energy dimension-6 four-fermion operators: for these, HEFT allows \( O(1) \) couplings, while in SMEFT they are suppressed by a factor \( v^2/\Lambda^2 \), where \( v \) is the Higgs vev. In this talk, I argue that (i) such non-SMEFT operators contribute to both \( b \rightarrow s H^\pm \ell^- \) and \( b \rightarrow c \tau^+ \nu_\tau \), transitions involved in the present-day \( B \) anomalies, (ii) the contributions to \( b \rightarrow s H^\pm \ell^- \) are constrained to be small, at the SMEFT level, and (iii) the contribution to \( b \rightarrow c \tau^+ \nu_\tau \) can be sizeable. I show that the angular distribution in \( B \rightarrow D^* (\rightarrow D \pi^+) \tau^- (\rightarrow \pi^- \nu_\tau) \bar{\nu}_\mu \) contains enough information to extract the coefficients of all new-physics operators. The measurement of this angular distribution can tell us if non-SMFT new physics is present.

I. SMEFT VS. HEFT

The Standard Model (SM) of particle physics explains almost all experimental data to date. There is no doubt that it is correct. This said, the SM is not complete: for example, it has no explanation for neutrino masses, dark matter and the baryon asymmetry of the universe. There must exist physics beyond the SM. And since no new particles have been seen at the LHC, this new physics (NP) must be heavy.

The modern view is that the SM is just the leading part of an effective field theory (EFT) (see, e.g., Refs. [1, 2]), obtained when this NP is integrated out at a scale of \( O(\text{TeV}) \). This EFT must respect the SM symmetry group \( SU(3)_C \times SU(2)_L \times U(1)_Y \).

But this raises the 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.

The question of whether the symmetry is realized linearly or nonlinearly can only be answered experimentally. To see how this can be done, one must compare power counting in SMEFT and in HEFT.

Consider a non-standard \( Z \bar{u}_R u_R \) coupling,
\[ g_z Z \bar{u}_R (\bar{u} \gamma^\mu P_R u_R) \]. Within HEFT, it has mass-dimension 4, so \( g_z \sim O(1) \). But within SMEFT, it arises at dimension 6 from \( \Lambda_z^2 (H^\dagger D_R H)(\bar{u} \gamma^\mu P_R u_R) \). Thus, \( g_z \sim v^2/\Lambda_z^2 \). There are other dimension-6 operators that do not involve the Higgs field (e.g., four-fermion operators). Their coefficients \( \sim \Lambda^{-2} \), where \( \Lambda \) is the scale of NP, \( \gtrsim O(\text{TeV}) \). Within SMEFT, the assumption is that \( \Lambda_h = \Lambda \). This implies that SMEFT predicts that \( g_z \) is considerably smaller than the value allowed by HEFT.

In order to test the SMEFT assumption, we must (i) identify operators whose power counting is different in SMEFT and HEFT, and (ii) find ways of measuring these operators. If it is found that the coefficient of such an operator is larger than what is predicted by SMEFT, this points to non-SMFT NP.

II. LEFT

As the title of the talk indicates, we want to test SMEFT with \( B \) decays. At this energy scale, \( O(m_b) \), the EFT is the LEFT (low-energy effective field theory), also known as WET, weak effective field theory), obtained when the heavier SM particles \( (W^\pm, Z^0, H, t) \) are also integrated out. (This is like the Fermi theory.)

In Ref. [14], a complete and non-redundant basis of LEFT operators up to dimension 6 is presented. We focus on those operators that conserve lepton and baryon number. 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 \( SU(2)_L \times U(1)_Y \). That is, they are not generated by dimension-6 SMEFT operators. These “non-SMFT operators” are the ones that interest us.

In Ref. [15], my collaborators and I examine the LEFT operators and identify eleven types of non-SMFT four-fermion operators: there are six four-quark operators, one four-lepton operator, and four (semileptonic) operators with two quarks and two leptons.

But this is just the first step; we must also find ways of measuring them.
III. THE B ANOMALIES

At the present time, there are discrepancies with the SM in measurements of a number of observables involving the semileptonic transitions \( b \to s\ell^+\ell^- \) (\( \ell = e, \mu \)) and \( b \to c\tau^-\bar{\nu}_\tau \) decays. These are the B anomalies (for a review, see Ref. [10]). Our list of non-SMEFT four-fermion operators includes contributions to these two types of decays. It is only natural to explore whether these two can be measured in tests of the B anomalies.

There are two dimension-6 non-SMEFT operators that contribute to \( b \to s\ell^+\ell^- \). Along with the dimension-8 SMEFT operators to which they are mapped at tree level, they are

\[
\begin{align*}
O_{cd}^{S,RR} & \equiv (\bar{\tau}_L p e_R e_R) (\bar{d}_{Lx} d_{Ri}) & \rightarrow & & Q_{\ell cd}^{(3)} & \equiv (\bar{\tau}_p e_R)(\bar{\tau}_q d_i) , \\
O_{cd}^{T,RR} & \equiv (\bar{\tau}_L p e_R e_R) (\bar{d}_L s_{\mu\nu} d_{Ri}) & \rightarrow & & Q_{\ell cd}^{(4)} & \equiv (\bar{\tau}_p s_{\mu\nu} e_R)(\bar{\tau}_q d_i H) .
\end{align*}
\]

Here, the Øs are dimension-6 four-fermion LEFT operators, that contribute to \( b \to s\ell^+\ell^- \). Along with the dimension-8 SMEFT operators to which they are mapped at tree level, they are

\[
\begin{align*}
\frac{4G_F}{\sqrt{2}} V_{ub} O_{V}^{LL} & - \frac{C_{V}^{LL}}{\Lambda^2} O_{V}^{LL} - \frac{C_{V}^{LR}}{\Lambda^2} O_{V}^{LR} , \\
- \frac{C_{S}^{LL}}{\Lambda^2} O_{S}^{LL} & - \frac{C_{S}^{LR}}{\Lambda^2} O_{S}^{LR} - \frac{C_{T}^{LR}}{\Lambda^2} O_{T} ,
\end{align*}
\]

with

\[
\begin{align*}
O_{V}^{LL,LR} & \equiv (\bar{\tau}\gamma^\mu P_L\nu)(\bar{c}\gamma_\mu P_{L,R}\bar{b}) , \\
O_{S}^{LL,LR} & \equiv (\bar{\tau} P_L\nu)(\bar{c} P_{L,R}\bar{b}) , \\
O_{T} & \equiv (\bar{\tau}\sigma^\mu\nu P_L\nu)(\bar{c}\sigma_{\mu\nu} P_{L,R}\bar{b}) .
\end{align*}
\]

But note: \( O_{V}^{LR} \) is the non-SMEFT operator of Eq. (2); its coefficient \( C_{V}^{LR} \) is suppressed by \( v^2/\Lambda^2 \) in SMEFT. For this reason, it is usually ignored when looking for NP in \( b \to c\tau^-\bar{\nu}_\tau \).

For example, fits to the \( b \to c\tau^-\bar{\nu}_\tau \) data are performed in Refs. [20 [21], but with \( O_{V}^{LR} \) excluded (precisely because it is a non-SMEFT operator). In Ref. [15], we redo the fit, including \( O_{V}^{LR} \). The results are shown in Table [1]. Although the best fit is provided by the scenario in which only \( C_{V}^{LL} \) is added, the fit remains acceptable when both \( C_{V}^{LL} \) and \( C_{V}^{LR} \) are allowed to be nonzero. And in this scenario, the best fit has \( C_{V}^{LR} = O(1) \). Such a large value is allowed within HEFT, but not SMEFT.

The bottom line is that a non-SMEFT value of \( C_{V}^{LR} \) is allowed by the present data. Furthermore – and this is the point of this talk – it can be measured.

TABLE I: Fit results for the scenarios in which \( C_{V}^{LL} \), \( C_{V}^{LR} \) or both \( C_{V}^{LL} \) and \( C_{V}^{LR} \) are allowed to be nonzero.

| New-physics coeff. | Best fit | \( p \) value (%) |
|---------------------|----------|-------------------|
| \( C_{V}^{LL} \)    | \(-3.1 \pm 0.7\) | 51                |
| \( C_{V}^{LR} \)    | \(2.8 \pm 1.2\)   | 0.3               |
| \( (C_{V}^{LL}, C_{V}^{LR}) \) | \((-3.0 \pm 0.8, 0.6 \pm 1.2\) | 35               |

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IV. MEASURING NON-SMEFT OPERATORS

Consider $B \to D^* \tau^- \bar{\nu}_\tau$. Because $B$ is a pseudoscalar meson, while $D^*$ is a vector, there are only four NP operators that contribute: $O_1^{LR}, O_2^{LR}, O_1^{LP}, O_2^{LP}$, $O_T$. This implies that there are seven NP parameters (four magnitudes, three relative phases).

In Ref. [22], it is proposed to measure the angular distribution in $B \to D^*(\to D\pi^-) \tau^- (\to \pi^- \nu_\tau) \bar{\nu}_\tau$. The differential decay rate is a function of five parameters: $q^2$ (the momentum squared of the $\tau^- \bar{\nu}_\tau$ pair), $E_\tau$ (the energy of the pion in $\tau^- \to \pi^- \nu_\tau$), and the three angles $\theta^*, \theta_\pi, \chi_\pi$ (see Fig. I). The data is separated into $q^2,E_\pi$ bins, and an angular analysis is performed in each bin.

The angular distribution can be written as

$$\sum_{i=1}^{9} f_i^R(q^2,E_\pi) \Omega_i^R(\theta^*, \theta_\pi, \chi_\pi) + \sum_{i=1}^{3} f_i^I(q^2,E_\pi) \Omega_i^I(\theta^*, \theta_\pi, \chi_\pi). \quad (6)$$

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

The key point is the following. There are twelve observables (angular functions) in each $q^2,E_\pi$ bin. (And there may well be several bins – the exact number will be decided by experiment.) But there are only seven NP parameters. This implies that all NP parameters can be extracted. If the value of $|C_1^{LR}|$ is found to be larger than that predicted by SMEFT, then not only will NP have been discovered, but it will have been determined that this is new, non-SMEFT NP.

Finally, we note that Ref. [23] argues that there are hints of NP in $b \to c \mu^- \bar{\nu}_\mu$. As with $b \to c \tau^- \bar{\nu}_\tau$, there are several dimension-6 four-fermion NP operators that contribute to $b \to c \mu^- \bar{\nu}_\mu$, including one non-SMEFT operator. This decay can be analyzed similarly to $b \to c \tau^- \bar{\nu}_\tau$: the angular distribution for $b \to c \mu^- \bar{\nu}_\mu$ described in Ref. [21] provides enough observables to fit for the coefficients of all dimension-6 NP operators, including the non-SMEFT one.

V. Recap

It is generally thought that the SM is the leading part of an EFT produced when the heavy NP is integrated out. Since the discovery of the Higgs boson, this EFT is usually taken to be the SMEFT. However, this is an assumption; the identity of the EFT must be determined experimentally.

One difference between HEFT and SMEFT is power counting: the coefficients of certain low-energy four-fermion operators are predicted to be considerably smaller in SMEFT than in HEFT. This suggests a simple test: find such an operator and measure its coefficient. If the value of the coefficient is found to be larger than that predicted by SMEFT, this implies that the NP operator is of non-SMEFT type.

At present, there are anomalies in $b \to s \bar{c} \ell^+ \ell^-$ and $b \to c \tau^- \bar{\nu}_\tau$ decays. Both of these receive contributions from non-SMEFT NP operators. In the case of $b \to s \bar{c} \ell^+ \ell^-$, the coefficients of such operators are constrained to be small, of SMEFT size. But the coefficient of the non-SMEFT $b \to c \tau^- \bar{\nu}_\tau$ operator $O_1^{LR}$ is still allowed by present data to be sizeable.

The angular distribution in $B \to D^*(\to D\pi^-) \tau^- (\to \pi^- \nu_\tau) \bar{\nu}_\tau$ provides enough observables to extract all NP parameters from a fit. If the coefficient of $O_1^{LR}$ is found to be larger than the SMEFT prediction, this will point to the presence of non-SMEFT NP.

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