On the anomalies recently observed in semileptonic B decays to the third family

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Abstract

The BABAR measurements of the ratios $\sigma^{D^*}/\sigma^{D}$ and $\tau^{D^*}/\tau^{D}$ deviate from the standard model expectations, while new results on the purely leptonic $B \to J/\psi \ell^+ \ell^-$ mode show a better consistency with the standard model. In a new physics scenario, one possibility to accommodate these two experimental facts consists in considering an additional tensor operator in the effective weak Hamiltonian. We study the effects of such an operator in a set of observables, in semileptonic $B \to D^*$ mode as well as in semileptonic $B$ and $D^*$ decays to excited positive-parity charmed mesons.

1) Experimental results

- By an accurate measurement of the ratios $R(D^*) = \frac{\sigma(D^*)}{\sigma(D)}$ and $\frac{\tau(D^*)}{\tau(D)}$ for the $B \to D$ decays into $D^*$ plus a lepton, the BABAR collaboration found a significant deviation from the standard model (SM) predictions.

- Is it a New Physics signal?

  a) The measurements of the ratios $\sigma(D^*)$ have been performed on different datasets collected during four run periods. The final result is the fit to the whole data sample.

  b) By studying the $y^*$ distribution on the $D^0$-D* plane, the possibility that the two measurements both agree with the SM expectations is excluded at 3.4σ level.

2) $g(D^*)$ ratios in the Standard Model

- The decay widths for the $D^*$ modes depend on several hadronic form factors, that reduce to the Isgur-Wise $f_1$ function in the heavy-quark limit.

  a) We have taken into account the radiative corrections at order α and $1/m_s$ mass corrections in the theoretical evaluation of $f_1$.

  b) We use as an input the experimental determination of $f_1$ obtained by BABAR (for the mode with a $D$ in the final state) and by the Belle collaboration (in the channel with a $D^*$).

- The measurement of $\sigma(D^*)$, which determines $f_1$, is divided by $\sigma(D)$ and $\tau(D)$, respectively.

- Moreover, recent experimental measurements show consistency with SM.

3) Theoretical explanation of the anomaly

- Does there exist a relationship between $N = 1/2$ and $N = 3/2$?

  a) In a New Physics (NP) scenario, it seems quite natural to explain the anomalies by introducing new scalars that couple to leptons proportionally to their masses (in such a way that a decay mode is enhanced). One of the simplest models in which this mechanism holds is the Two-Higgs-Doublet Model (of type II), where the scalar field is a charged Higgs.

  ... however the BABAR results exclude these scenarios!

- Can we imagine a different New Physics effect?

  a) Let us consider a scenario in which only the semileptonic modes are enhanced, and

  b) and investigate several observables which could eventually discriminate between the SM and the NP scenario.

Our proposal for an effective Hamiltonian beyond the Standard Model is

$$H^{eff} = \frac{1}{2}v^2\left(\gamma_5(1-\gamma_5)h^{\tau}f_{N}^{T}\right)$$

SM

$$H^{eff} = \frac{1}{2}v^2\left(\gamma_5(1-\gamma_5)h^{\tau}f_{N}^{T}\right)$$

NF with a tensor operator

- $\rho^{N}$ is a complex effective coupling and we set it to zero for the light leptons, then $\rho^{N} \equiv \rho^T$.

- Such an operator could naturally emerge in models with leptoquark.

- All the observables that we analyzed depend on this new tensor coupling, whose range of variability is constrained by the experimental measurements of the ratios $\sigma(D^*)$.

4) Constraints on the NF parameters

- What are the allowed regions on the complex plane of the $\rho^T$ parameter, for which it is possible to fit both $\sigma(D)$ and $\sigma(D^*)$?

  a) The bigger annulus result from the experimental datum on $\sigma(D^*)$ (respectively 0.1σ and 2σ), while the smaller ones have been determined from the measurement of $\sigma(D^*)$ (1σ and 2σ).

  b) The overlap region can be parameterized as

$$\rho^T = \frac{\chi}{\chi + \chi_T}$$

where

$$\chi_T = \frac{1}{16\pi} \left[\ln(\chi_T) - 0.38\right]$$

- Strategy varying $\rho^T$ in the experimental constrained region, we get prediction on several observables.

5) Measurements vs predictions for several observables

- The BABAR differential decay widths (normalized to the total number of events) for the two channels with $D^*$ and $D$ do not show a significant deviation with respect to both the SM and NP scenario.

- Forward-Backward Asymmetry: in the $D^*$ case, a significant shift of the position of its zero ($q^2 = 8.7$ GeV$^2$) with respect to SM ($q^2 = 6.2$ GeV$^2$).

6) Predictions for the channels with $D^{**}$ in the final states

- $D^{**}$ are excited positive-parity charmed mesons. The semileptonic $B$ decays to these channels can confirm NP scenarios like the one proposed here.

  a) These states can be collected into two doublets:

$$D^{**}\rightarrow D^{*} \rightarrow D^* \rightarrow B^{**}$$

- To describe the $B \to D^{**}$ decays let us use the heavy quark limit, in which the form factors can be parameterized by only one Isgur-Wise $f_1$ function:

$$\frac{1}{2}v^2\left(\gamma_5(1-\gamma_5)h^{\tau}f_{N}^{T}\right)$$

- $\phi^T$ is the angle between the charged lepton and $D^*$ in the leptonic pair rest frame.

- Correlations among the observables $\sigma(D^{**})$ and $\sigma(D^{**})$ for each spin doublet:

We may observe an important modification of the correlations between the ratios $\sigma(D^{**})$, both in the strange modes and in the ones without strangeness.

References