Study of Anomalies in Exclusive B Meson Semileptonic Decays

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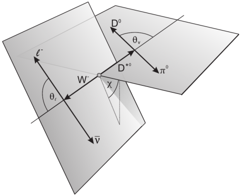
SAPIENZA UNIVERSITÀ DI ROMA
UNI GRAZ
FWF Der Wissenschaftsfonds.
NAWI Graz Natural Sciences

Introduction

We study the anomalies observed in the exclusive semileptonic decays of the B into the D and D^* mesons. In particular we focus on

- The basic aspects of the kinematics of semileptonic decays.
- Recent unfolded Belle results that allows us to extract the matrix element V_{cb}.
- Discrepancy between the inclusive and exclusive determinations of V_{cb}.
- The quantity R_{D^*}, which is systematically larger than the standard model prediction.
- The effects of a pseudo scalar effective operator, since it gives an enhancement to third lepton generation decays.

Kinematics Angles



- The helicity angles used are θ_l, θ_v and χ.
- The angles θ_l, θ_v are defined in the center of mass of the virtual W^- and D^*.
- The angle θ_l is defined by the directions of the charged lepton.
- Similarly θ_v is defined using the direction of the D^*.
- The angle χ is obtained between the two planes where the θ_l and θ_v are defined.

Fourfold Differential Decay Amplitude

$$
\begin{aligned}
\frac{d\Gamma(B \to D^*(\to D\pi)l\nu)}{dq^2 d\cos\theta_v d\cos\theta_l d\chi} = & \frac{3G_F^2|V_{cb}|^2|\mathbf{q}|q^2}{8(4\pi)^4 m_B^2}\{(1-\cos\theta_l)^2\sin^2\theta_v|H_{++}|^2 \\
& + (1+\cos\theta_l)^2\sin^2\theta_v|H_{--}|^2 \\
& + 4\sin^2\theta_l\cos^2\theta_v|H_{00}|^2 \\
& - 2\sin^2\theta_l\sin^2\theta_v\cos 2\chi H_{++}H_{--} \\
& - 4\sin\theta_l(1-\cos\theta_l)\sin\theta_v\cos\theta_v\cos\chi H_{++}H_{00} \\
& + 4\sin\theta_l(1+\cos\theta_l)\sin\theta_v\cos\theta_v\cos\chi H_{--}H_{00}\}
\end{aligned}
\tag{1}
$$

BGL Parametrization

In the paper of Boyd et al. the matrix elements are parametrized as:

$$\langle D^*|V_\mu|B\rangle = ig(w)\epsilon_{\mu\alpha\beta\gamma}\epsilon^{\alpha} p_B^{\beta} p_{D^*}^{\gamma} \,, \tag{2}$$

$$\langle D^*|A_\mu|B\rangle = f(w)\epsilon_\mu + (\epsilon\cdot p_B)[a_+(w)(p_B+p_{D^*})_\mu + a_-(w)(p_B-p_{D^*})_\mu] \,. \tag{3}$$

The helicity amplitudes are parametrized as

$$H_{00}(w) = \frac{\mathcal{F}_1(w)}{\sqrt{q^2}} \tag{4}$$

$$H_{\pm\pm} = f(w) \mp m_B m_{D^*}\sqrt{w^2-1}g(w)\,, \tag{5}$$

where the factor $\mathcal{F}_1$ is defined by

$$\mathcal{F}_1(w) = \frac{1}{m_{D^*}}[2m_B^2 m_{D^*}^2(w^2-1)a_+(w) + m_B m_{D^*} w f(w)]\,. \tag{6}$$

We write the expansion for the three form factors we will be using as

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n \tag{7}$$

$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{N} b_n z^n \tag{8}$$

$$\mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{N} c_n z^n \tag{9}$$

The outer functions ϕ_i are essentially phase space factors, while the inner functions P_i are made of products of Blaschke factors, which remove poles associated to the production of excited B_c meson states, with mass less than $m_B + m_{D^*}$.

CLN Parametrization

The w dependence of the universal form factor and the ratios are heavily constrained by the HQET, and have the following form, in terms of five parameters: $h_{A_1}(1)$, which is the universal form factor at minimum recoil, $R_i(1)$ that are the ratios at minimum recoil, and $\rho^2_{D^*}$, which is a single parameter of slope

$$h_{A_1}(w) = h_{A_1}(1)(1 - 8\rho^2_{D^*}z + (53\rho^2_{D^*} - 15)z^2 - (231\rho^2_{D^*} - 91)z^3) \tag{10}$$

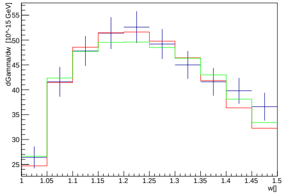
$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2 \tag{11}$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2 \tag{12}$$

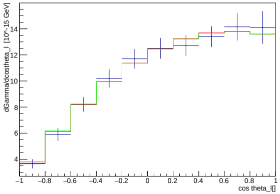
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2 \; . \tag{13}$$

Histograms with CLN and BGL fits

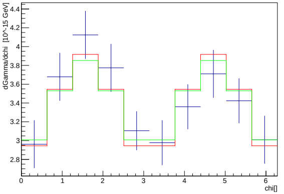
Unfolded Recoil Semileptonic B Decay spectre



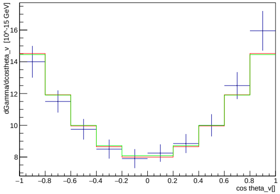
Unfolded cos theta_l Semileptonic B Decay spectre



Unfolded chi Semileptonic B Decay spectre



Unfolded cos theta_v Semileptonic B Decay spectre



CLN Results

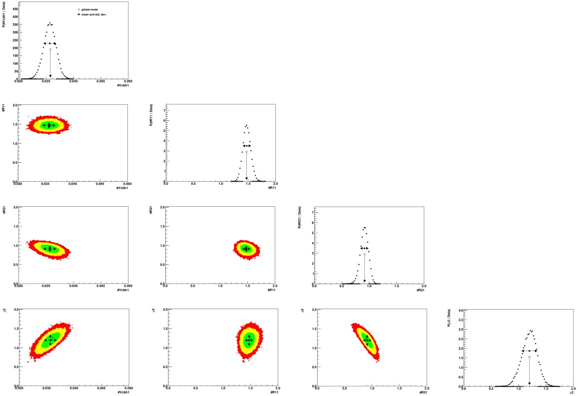


Figure: Marginalized posterior PDFs and correlation diagrams of the CLN parameters. The green, yellow and red bands show 1, 2 and 3 σ confidence intervals.

BGL Results

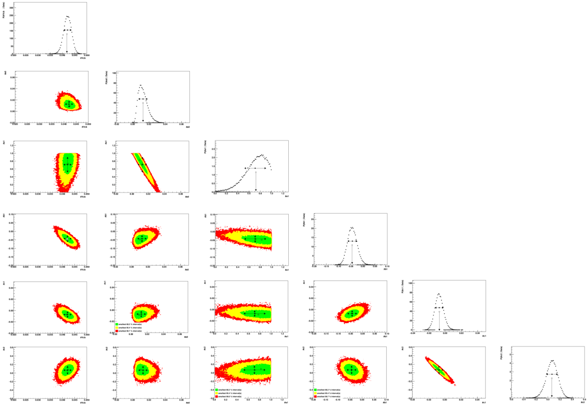


Figure: Marginalized posterior PDFs and correlation diagrams of the BGL parameters. The green, yellow and red bands show 1, 2 and 3 σ confidence intervals.

CLN	Mean Values $\pm$ Errors
$\|V_{cb}\| h_{A_1}(1)$	$(35.662 \pm 1.132)\ 10^{-3}$
ρ^2_{D*}	1.196 ± 0.140
$R_1(1)$	1.474 ± 0.072
$R_2(1)$	0.9105 ± 0.0723

Parameter	unfolded result
$\|V_{cb}\| \times 10^3$	38.2 ± 1.5
ρ^2_{D*}	1.17 ± 0.15
$R_1(1)$	1.39 ± 0.09
$R_2(1)$	0.91 ± 0.08

BGL	Mean Values $\pm$ Errors
$\|V_{cb}\|$	$(42.1 \pm 1.2)\ 10^{-3}$
a_0	0.0126 ± 0.0056
a_1	0.71 ± 0.19
b_1	-0.0428 ± 0.020
c_1	-0.0071 ± 0.0053
c_2	0.066 ± 0.094

The best-fit values from fitting the unfolded spectra from the Belle collaboration is shown. The BGL result is also compatible with the results that come from the inclusive determination of V_{cb}

$$|V_{cb}| = (42.00 \pm 0.65)10^{-3} \quad (14)$$

Effective New Physics Hamiltonian

We parametrize the new operators with five coefficients g_i, $i = V, A, S, P, T, T_5$ that multiplies operator densities not present in the SM. Obviously, putting $g_i = 0$ will give the SM result, with the $V - A$ form for the hadronic part

$$\begin{aligned}\mathcal{H}_{\text{eff}} &= \frac{G_F}{\sqrt{2}} V_{cb}\; H_\mu L^\mu + \text{h.c} \\ &= \frac{G_F}{\sqrt{2}} V_{cb} \Big[(1 + g_V)\bar{c}\gamma_\mu b + (-1 + g_A)\bar{c}\gamma_\mu\gamma_5 b + \frac{g_S}{m_B}\; i\partial_\mu(\bar{c}b) \\ &\quad + \frac{g_P}{m_B}\; i\partial_\mu(\bar{c}\gamma_5 b) + \frac{g_T}{m_B}\; i\partial^\nu(\bar{c} i\sigma_{\mu\nu} b) + \\ &\quad \frac{g_{T5}}{m_B}\; i\partial^\nu(\bar{c} i\sigma_{\mu\nu}\gamma_5 b) \Big] \; \bar{\ell}\gamma^\mu(1 - \gamma_5)\nu_\ell + \text{h.c}\,. \end{aligned} \tag{15}$$

Using the current value of $|V_{cb}|$ given by the UTfit collaboration

$$|V_{cb}| = 0.04229 \pm 0.0057 \tag{16}$$

we fit the data adding the additional factors g_V and g_A one at a time. We use the form factors obtained during the extrapolation of $|V_{cb}|$. We obtain a good fit with the values

$$g_V = -0.01794 \pm 0.03926 \tag{17}$$

$$g_A = 0.05603 \pm 0.01838 \; . \tag{18}$$

These results are obtained without giving the error we obtained on the parameters of the CLN parametrization, that we have fitted in the previous chapter. It isn't possible to extract information from these data about the presence of deviations from the usual $V - A$ interaction if we add the error on the form factors.

The R_D and R_{D^*} anomalies

The most statistically significant deviation involving B meson decays, at almost 4σ deviation from the SM prediction, is present in the two quantities R_D and R_{D^*}, defined as

$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)} \tau \bar{\nu}_\tau)}{\Gamma(\bar{B} \to D^{(*)} l \bar{\nu}_l)} \tag{19}$$

where l is a light lepton: $l = e, \mu$. As reported by HFAG collaboration, current averages on these quantities are

$$\begin{aligned} R_D &= 0.407 \pm 0.039 \pm 0.024 \\ R_{D^*} &= 0.304 \pm 0.013 \pm 0.007 \end{aligned} \tag{20}$$

The differential width for the process $B \to D^* \tau \nu_\tau$, can be written as

$$\frac{d\Gamma_\tau}{dw} = \frac{d\Gamma_{\tau,1}}{dw} + \frac{d\Gamma_{\tau,2}}{dw} \tag{21}$$

where

$$\frac{d\Gamma_{\tau,1}}{dw} = \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma}{dw} \tag{22}$$

$$\frac{d\Gamma_{\tau,2}}{dw} = k\sqrt{w^2 - 1}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{3}{2} m_\tau^2 |H_t|^2 \tag{23}$$

We can calculate the ratio (19) for the vector meson decay splitting the contributions in two parts, given $R_{D^*} = R_{\tau,1}(D^*) + R_{\tau,2}(D^*)$:

$$R_{\tau,1}(D^*) = \frac{\int_1^{w_{\tau,max}} dw \; d\Gamma_{\tau,1}/dw}{\int_1^{w_{max}} dw \; d\Gamma_\tau/dw} \; ; \; R_{\tau,2}(D^*) = \frac{\int_1^{w_{\tau,max}} dw \; d\Gamma_{\tau,2}/dw}{\int_1^{w_{max}} dw \; d\Gamma_\tau/dw} \tag{24}$$

Using the form factors obtained during the extrapolation of $|V_{cb}|$ with the BGL parametrization, we can obtain easily $R_{\tau,1}(D^*)$ with value

$$R_{\tau,1}(D^*) = 0.230 \pm 0.017\,. \tag{25}$$

Using the experimental value of $R^{exp}(D^*)$, we can estimate the value of $R_{\tau,2}$, obtaining

$$R_{\tau,2} = 0.080 \pm 0.028\,. \tag{26}$$

The result we obtain for the pseudo-scalar operator coefficient is

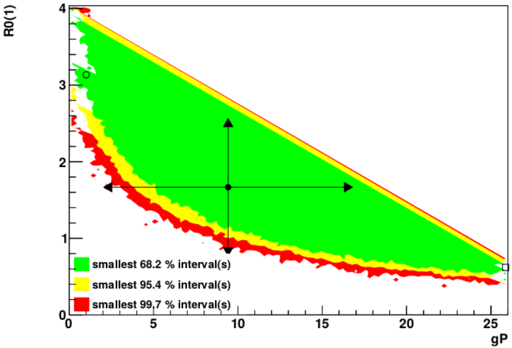
$$g_P(m_b) = 9.058 \pm 4.666\,. \tag{27}$$

As previously pointed out, the relations obtained in HQET aren't always reliable. If we let $R_0(1)$ vary over its standard value, without adding the other pseudo-scalar operator, we obtain a good fit with the value

$$R_0(1) = 3.3923 \pm 0.343\,. \tag{28}$$

The central value is roughly three times bigger than the one obtained by calculations in HQET.

Correlation between $R_0(1)$ and g_P



It is possible to visualize the correlation between g_P and $R_0(1)$, when are both included and free to vary.

Conclusions

- The large discrepancy between the results of $|V_{cb}|$ is a signal that the parameters used in CLN are too constrained, without a reliable estimate of their uncertainties. With the improved precision of the recent data, this kind of procedure can't be used for an analysis.
- We found that, with the actual theoretical precision of the form factors, it isn't possible to extract significative informations about deviations from the vectorial or axial channel from the data with massless leptons.
- We analyzed the anomaly of the observable R_{D^*}. This could be caused by the presence of a new physics pseudo-scalar operator, but to estimate his contribution, it is necessary to use constraints from HQET. We find a nonzero value for the Wilson coefficient, but it is surely necessary to pursue a better understanding of nonpertubative QCD to have a clear understanding of this anomaly.

Thank you for your attention!