UNIVERSITÄT SIEGEN

$B \to D^{(*)}$ form factors and V_{cb} determination

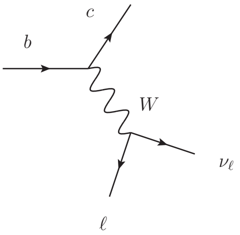
Marzia Bordone
Universität Siegen

13th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"
26.11.2019

Importance of (semi-)leptonic decays

In the Standard Model

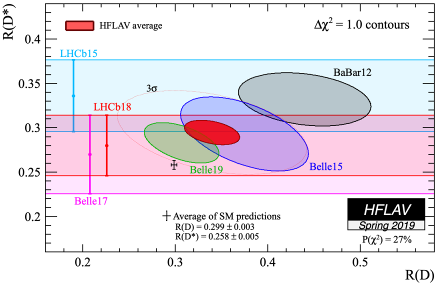
- Tree-level processes $\sim G_F^2 |V_{ij}|^2 \mathcal{F}^2$
- They are perfect processes to extract $|V_{ij}|$
- Branching ratios are usually large



Beyond the Standard Model

- Moderate NP can be seen if we understand the SM predictions precisely
- Can test structures $\neq$ from SM ones (especially for heavy leptons)

Motivation



- Avarage of BaBar, Belle, LHCb data yields $3-3.5\sigma$ deviation with the SM

NP $\sim 10-15\%$ of a SM tree decay $\Rightarrow$ huge effect

- If NP interfere with SM we need it to be 10%
- If NP doesn't interfere with SM, we need it to be a 40% effect

- Check SM predictions! $\Leftarrow$ main topic of this talk
- NP analysis: rely on hadronic inputs

The longstanding V_{cb} puzzle

- The inclusive determination in extremely under control (up to $\mathcal{O}(1/m_b^3, \alpha_2/m_b^2, \alpha_s^2)$)

$$V_{cb}^{\text{incl}} = (42.00 \pm 0.64) \times 10^{-3}$$

- The exclusive determination is less clear and depends on different data set/assumptions for the form factors
- Unfolded differential measurements made available by Belle: allows fits with different parametrisations for the form factors are possible
- Especially for $B \to D^*$ decays, a tension $\sim 2\sigma$ with the inclusive determination remains
- NP explanations are disfavoured [Jung,Straub,'18]

Hadronic Matrix Elements

$$\langle D|\bar{c}\,\Gamma_{\mu_1\mu_2}b|\overline{B}\rangle = \sum_i S^i_{\mu_1\mu_2}F_i(q^2)$$

$$\langle D^*(\lambda)|\bar{c}\,\Gamma_{\mu}b|\overline{B}\rangle = \sum_\lambda \sum_i \epsilon^\alpha(\lambda)S^i_{\alpha\mu}F_i(q^2)$$

Form Factor: scalar function which encodes the non-perturbative dynamics

- $B \to D$: 2FF + 1 tensor for NP
  - vector current: 2 FF
  - tensor current: 1 FF
- $B \to D^*$: 4FF + 3 tensor for NP
  - vector current: 1 FF
  - axial-vector current: 3 FF
  - tensor current: 3 FF

Hadronic Matrix Elements: Lattice

Lattice: discretised space-time

- prediction for high q^2
- unstable particles (D^*) are problematic

State of the art:

- $B \to D$: complete set of SM FFs calculated [HPQCD, 2015, Fermilab/MILC, 2015 FLAG, 2016]
- $B \to D^*$: only few prediction at the zero recoil point [Fermilab/MILC, 2014, HPQCD, 2017]
- preliminary results shown at Lattice 19 [Talk by A. Vaquero]

More theory inputs needed

HQET in a nutshell

- QCD distinguishes among flavour only through masses
- $b \to c$: the partonic transition involves only heavy quarks
- in the limit $m_{b,c} \to \infty$ but $m_c/m_b =$ finite

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_\infty + \mathcal{O}(1/m_Q)$$

  and $\mathcal{L}_\infty$ is independent of the heavy quark masses

- HQET's spin-flavour symmetry relates the various form factors, with breaking between symmetry relations suppressed by powers of $1/m_Q$

To leading power the form factors are all proportional to a single Isgur-Wise function $\xi(w)$

- $\xi(w)$ is the same for any $b \to c$ transitions involving $B^{(*)}$ and $D^{(*)}$.

The $B \to D^*$ case

How do we get informations on the $B \to D^*$ form factors?

- HQET + α_s and $1/m_{b,c}$ corrections + data inputs from Belle

  [Fajfer, Kamenik, Nisandzic, 2012]

- We can also use dispersive bounds to set contraints on the form factors

  [Boyd, Grinstein,Lebed, '95
  Caprini, Lellouch, Neubert, '97]

- HQET + dispersive bounds + data

  [Bigi, Gambino, Schacht, 2017
  Bernlochner, Ligeti, Papucci, Robinson, 2017]

Is there a way to parametrise form factors without using data?

BGL vs CLN parametrisations

CLN [Caprini, Lellouch, Neubert, '97]

- Expansion of FFs using HQET
- $1/m_{b,c}$ corrections included
- Expansion of leading IW function up to 2nd order in $(w-1)$

BGL [Boyd, Grinstein, Lebed, '95]

- Based on analyticity of the form factors
- Expansion of FFs using the conformal variable z
- Large number of free parameters

Our approach

Working assumption:

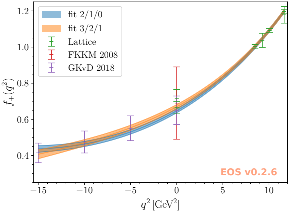
- We expand the FFs using HQET
- We introduce a **consistent** power counting: $\frac{\alpha_s}{\pi} \sim \frac{\Lambda_{QCD}}{2m_b} \sim \frac{\Lambda_{QCD}^2}{4m_c^2}$
  - full $1/m_c^2$ terms **must** be introduced
  - available only partially **[Jung, Straub,'18]**
- We use the **full set** of unitary bounds for all the decays $B^{(*)} \to D^{(*)}$

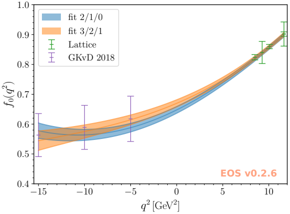
Inputs:

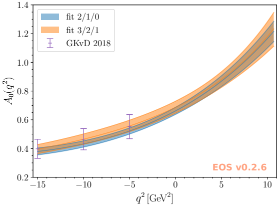
- Lattice points for $B \to D$
- Zero-recoil lattice points for $B \to D^*$
- QCD sum rules for subleading Isgur-Wise Functions
- Introduce new LCSR results **[Gubernari, Kokulu, van Dyk, 2018]**

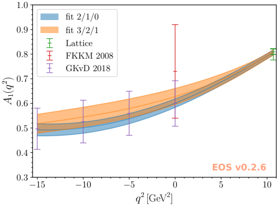
Fit results for the form factors

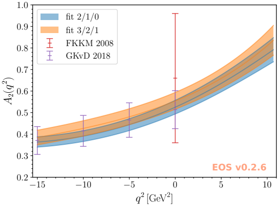
[MB, Jung, van Dyk, 1907.xxxx]



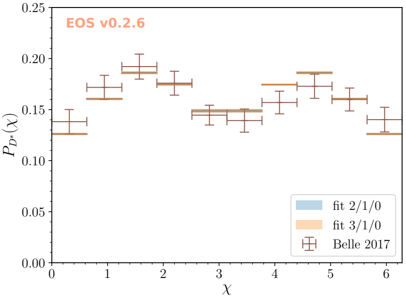


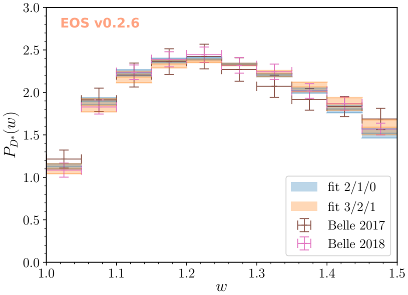


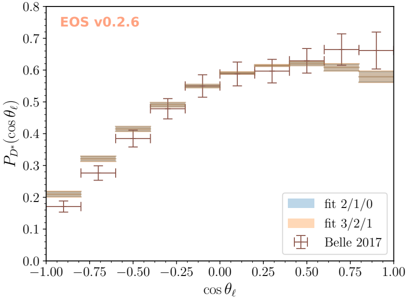




Comparison with kinematical distributions







good agreement with kinematical distributions

Predictions in the 321 fit model

[MB, Jung, van Dyk, 1908.09398]

	HFLAV	Our predictions
R_D	0.299 ± 0.003	0.298 ± 0.003
R_{D^*}	0.258 ± 0.005	0.247 ± 0.006

Predictions in the 321 fit model

[MB, Jung, van Dyk, 1908.09398]

	HFLAV	Our predictions
R_D	0.299 ± 0.003	0.298 ± 0.003
R_{D^*}	0.258 ± 0.005	0.247 ± 0.006
V_{cb}^D	$(39.18 \pm 1.00) \times 10^{-3}$	$(40.7 \pm 1.2) \times 10^{-3}$
$V_{cb}^{D^*}$	$(38.71 \pm 0.75) \times 10^{-3}$	$(39.3 \pm 1.7) \times 10^{-3}$

Predictions in the 321 fit model

[MB, Jung, van Dyk, 1908.09398]

	HFLAV	Our predictions
R_D	0.299 ± 0.003	0.298 ± 0.003
R_{D^*}	0.258 ± 0.005	0.247 ± 0.006
V_{cb}^D	$(39.18 \pm 1.00) \times 10^{-3}$	$(40.7 \pm 1.2) \times 10^{-3}$
$V_{cb}^{D^*}$	$(38.71 \pm 0.75) \times 10^{-3}$	$(39.3 \pm 1.7) \times 10^{-3}$

1σ and 1.5σ from incl. V_{cb}

$V_{cb}^{incl.} = (42.00 \pm 0.64) \times 10^{-3}$

- adding shape informations shifts slightly the central values and shrinks the errors

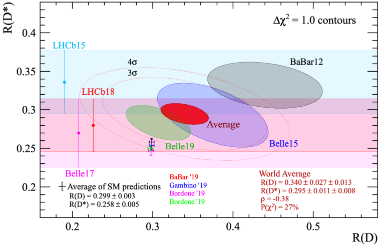
Summary

Our approach is based on:

- a HQET based parametrisation of the $B \to D$ and $B \to D^*$ form factors
- power corrections up to $\mathcal{O}(1/m_c^2)$
- inputs from lattice, QCD sum rules, update LCSR
- all set of unitarity constraints

We obtain the following:

- results are in agreement with kinematical distributions
- interesting predictions for phenomenological quantities



Appendix

HQET in a nutshell

- In HQET it is convenient to work with **velocities** instead of momenta
- Instead of q^2 we use the dimensionless variable $w = v_B \cdot v_{D^*}$
- When the $B(b)$ decays such that the $D^*(c)$ is at rest in the $B(b)$ frame

$$v_B = v_{D^*} \qquad \Rightarrow \qquad w = 1$$

- The brown muck doesn't realise that anything changed
- At zero recoil, the leading IW function is **normalized**

$$\xi(w = 1) = 1$$

V_{cb} and NP

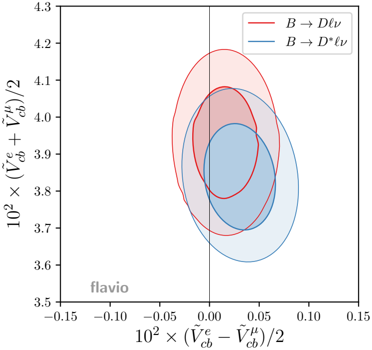
[Jung, Straub 2018]

- If we allow LFUV between μ and electrons

$$\tilde{V}_{cb}^{\ell} = V_{cb}(1 + C_{V_L}^{\ell})$$

- Fitting data from Babar and Belle

$$\frac{\tilde{V}_{cb}^{e}}{\tilde{V}_{cb}^{\mu}} = 1.011 \pm 0.012$$



$$\frac{1}{2}(\tilde{V}_{cb}^{e} + \tilde{V}_{cb}^{\mu}) = (3.87 \pm 0.09)\%$$

$$\frac{1}{2}(\tilde{V}_{cb}^{e} + \tilde{V}_{cb}^{\mu}) = (0.022 \pm 0.023)\%$$

Motivation

Anatomy of the ratios

$$\frac{\mathrm{d}\Gamma_\tau}{\mathrm{d}q^2} = \frac{\mathrm{d}\Gamma_{\tau,1}}{\mathrm{d}q^2} + \frac{\mathrm{d}\Gamma_{\tau,2}}{\mathrm{d}q^2}$$

$$\frac{\mathrm{d}\Gamma_{\tau,1}}{\mathrm{d}q^2} = \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2\left(1 + \frac{m_\tau^2}{2q^2}\right) \qquad R_{D^{(*)}}^{\tau,1} = \frac{\int_{m_\tau^2}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma_{\tau,1}}{\mathrm{d}q^2}}{\int_0^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}}$$

$$\frac{\mathrm{d}\Gamma_{\tau,2}}{\mathrm{d}q^2} = \Gamma_0 \, \frac{m_\tau^2}{q^2} c_0 \qquad R_{D^{(*)}}^{\tau,2} = \frac{\int_{m_\tau^2}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma_{\tau,2}}{\mathrm{d}q^2}}{\int_0^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}}$$

$$R_D^{\tau,1} = 0.176 \qquad R_D^{\tau,2} = 0.123$$

$$R_{D^*}^{\tau,1} = 0.232 \qquad R_{D^*}^{\tau,2} = 0.028$$

The contribution of $R_{D^*}^{\tau,2}$ in the error budget is small

The z-expansion

We can map the variable w into the conformal variable z:

$$z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} - \sqrt{2}}$$

- Easier implementation of unitarity and analiticity
- The value of $|z|$ is expected to be small $\Rightarrow$ better convergence of the expansion
- We can also combine HQET and dispersive bounds

The effect on $R_{D^{(*)}}$

R_D	0.299 ± 0.011	1503.07237 (FNAL/MILC)
	0.300 ± 0.008	1505.03925 (HPQCD)
	0.299 ± 0.003	1703.05330
	0.299 ± 0.004	1703.09977
$R_{D^{(*)}}$	0.252 ± 0.003	1203.2654
	0.257 ± 0.003	1703.05330
	$0.258^{0.010}_{-0.009}$	1707.09509
	0.257 ± 0.005	1703.09977

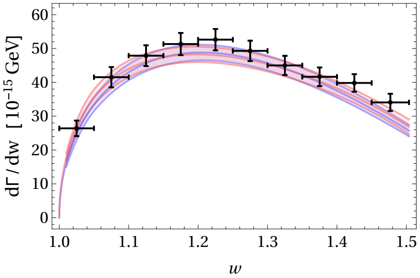
BGL vs CLN

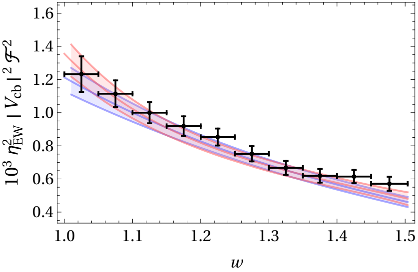
- Both BGL and CLN parametrisation of form factors rely on using unitarity arguments.

[Boyd, Grinstein, Lebed, '95

Caprini, Neubert, Lellouch, '98]

- CLN relies on HQET.
- Unfolded distributions from Belle allowed to repeat an independent fit.





BGL has a more conservative error

Provides better agreement with inclusive V_{cb}

Motivation

If I assume $\Lambda_{\text{NP}} >> v$: the SM gauge group is not broken up to Λ_{NP}

I can use SMEFT and match it to the WET

$$C_{V_L}^{\ell\ell'} = -\, v^2 \frac{V_{ci}}{V_{cb}} C_{lq}^{(3)\ell\ell' i3} + v^2 \frac{V_{ci}}{V_{cb}} C_{\phi q}^{(3)i3} \delta_{\ell\ell'} \qquad C_{V_R}^{\ell\ell'} = +\, \frac{v^2}{2} C_{\phi ud}^{23} \delta_{\ell\ell'}$$

$$C_{S_R}^{\ell\ell'} = -\, \frac{v^2}{2} \frac{V_{ci}}{V_{cb}} C_{ledq}^{\ell\ell' 3i} \qquad C_{T}^{\ell\ell'} = -\, \frac{v^2}{2} \frac{V_{ci}}{V_{cb}} C_{lequ}^{(3)\ell\ell' 3i}$$

$$C_{S_L}^{\ell\ell'} = -\, \frac{v^2}{2} \frac{V_{ci}}{V_{cb}} C_{lequ}^{(1)\ell\ell' 3i}$$

The WC $C_{V_R}^{\ell\ell'}$ must be flavour universal and diagonal

The coefficients might be constrained by different flavour processes