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

Marzia Bordone

Universität Siegen

Cortona Young

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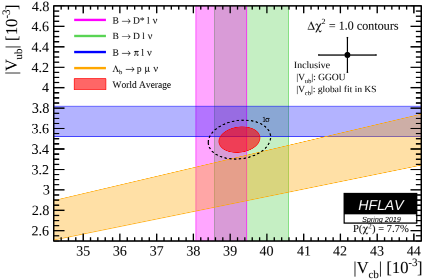
UNIVERSITÄT SIEGEN

Inclusive vs Exclusive V_{cb}

$$\mathcal{L}_{\mathsf{SM}} \supset \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Gamma^{\mu} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_{\mu}^{+}$$

- V_{cb} is a key element to test CKM Unitarity triangles
- Important input to evaluate many observables (e.g. ϵ'/ϵ)



- Inclusive: $B \to X_c \ell \bar{\nu}$

[P. Gambino, K. J. Healey, S. Turczyk, '16]

$$V_{cb}^{\mathsf{incl}} = (42 \pm 0.65) \times 10^{-3}$$

- Exclusive: $B \to D\ell\bar{\nu}$ and $B \to D^{*}\ell\bar{\nu}$

No general consensus yet, depends highly on the data set used and the assumptions for the hadronic decays

Inclusive vs Exclusive V_{cb}

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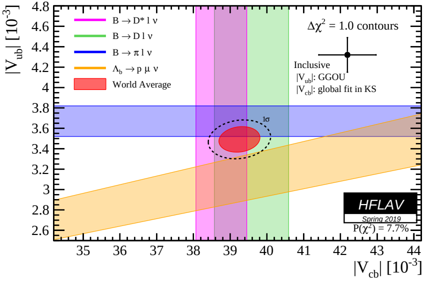

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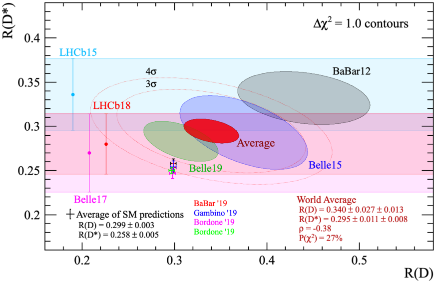
R_D and R_{D^*}

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

- Measure of the universality between τ/ℓ
- In the SM $\mathcal{B}(B \to D^{(*)}\mu\bar{\nu}) \sim \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})\phi(\tau)$
- Ratio reduces hadronic uncertainties



- $3.x\,\sigma$ deviation w.r.t. SM
- possible first signs of new physics
- more work on the SM prediction is needed

Hadronic Matrix Elements

- Hadronic decays $\to$ non perturbative dynamics
- **Form factors** encode the non-perturbative dynamics

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

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

$$q^2 = (p_B - p_{D^{(*)}})^2$$

- $B \to D$: 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
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10 independent functions to be determined

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]

Hadronic Matrix Elements: non-lattice methods

Evaluate form factors through dispersive analysis

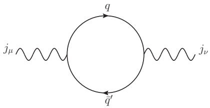
- QCD sum rules
- Light Cone Sum Rules

Parametrise the form factors using EFTs

- Heavy Quark Effective Theory: expansion of QCD Lagrangian for heavy quarks

  - The form factors are parametrised as expansions in $1/m_{b,c}$
  - Reduce the number of independent form factors
  - The 10 form factors are correlated through HQET relations
  - HQET relates all the form factors in $B^{(*)} \to D^{(*)}$ decays

Unitarity Bounds



$$= i\int d^4x\, e^{iqx}\langle 0|T\left\{j_\mu(x), j_\nu^\dagger(0)\right\}|0\rangle = (g_{\mu\nu} - q_\mu q_\nu)\Pi(q^2)$$

- If $q^2 \ll m_b^2$ we can calculate $\Pi(q^2)$ via perturbative techniques $\Rightarrow \chi(0)$
- Dispersion relations link Im $\left(\Pi(q^2)\right)$ to sum over matrix elements

$$\sum_i |F_i(0)|^2 < \chi(0)$$

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

- The sum runs over <u>all</u> possible states hadronic decays mediated by a current $\bar{c}\Gamma_\mu b$
    - The unitarity bounds are more effective the most states are included in the sum
    - The unitarity bounds introduce correlations between FFs of different decays
    - $B_s \to D_s^{(*)}$ decays are expected to be of the same order of $B_{u,d} \to D_{u,d}^{(*)}$ decays due to $SU(3)_F$ simmetry

Our approach

- We expand the FFs using HQET
- We introduce a **consistent** power counting: $\epsilon^2 \sim \frac{\alpha_s}{\pi} \sim \frac{\bar{\Lambda}}{2m_b} \sim \frac{\bar{\Lambda}^2}{4m_c^2}$
  - full $1/m_c^2$ terms **must** be introduced
  - available only partially [Jung, Straub,'18]
  - The FFs are expanded in the conformal variable z

$$F_i = \sum_n F_i^{(n)} z^n$$

  - The order at which we the FFs is determined by comparing different fits
- We use the of unitary bounds for all the decays $B^{(*)} \to D^{(*)}$

[MB, Jung, van Dyk, Eur. Phys. J. C 80, 74 (2020)]

Inputs

- Lattice points for $B \to D$

  [HPQCD 2015, Fermilab/MILC 2015, FLAG 2016]

- Zero-recoil lattice points for $B \to D^*$

  [Fermilab/MILC 2014, HPQCD 2017]

- QCD sum rules for subleading Isgur-Wise Functions

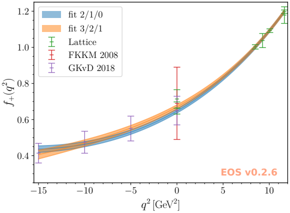
  [Ligeti, Nir, Neubert, '92, '93]

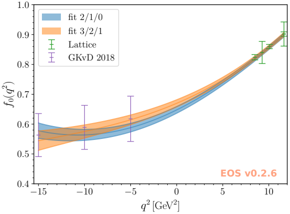
- Introduce new LCSR results

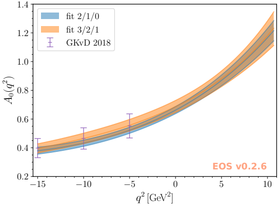
  [Gubernari, Kokulu, van Dyk, 2018]

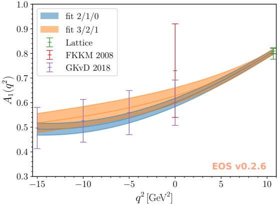
Fit results

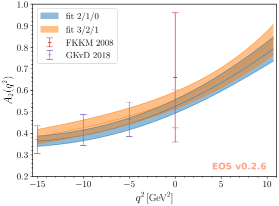
[MB, Jung, van Dyk, Eur. Phys. J. C 80, 74 (2020)]



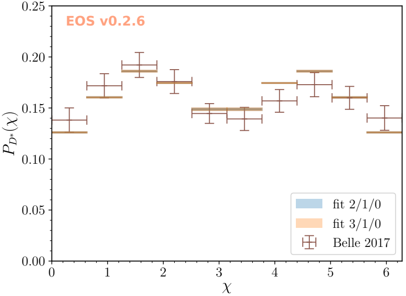


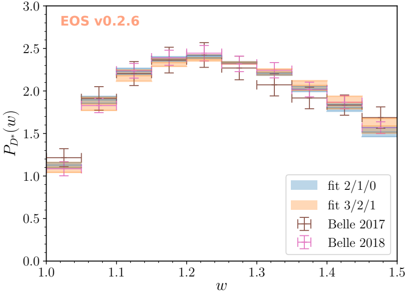


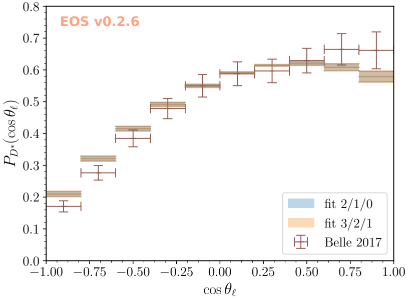




Comparison with kinematical distributions







good agreement with kinematical distributions

The $B_s \to D_s^{(*)}$ form factors

How to parametrise $B_s \to D_s^{(*)}$ form factors?

- Unitarity bounds correlate the $B^{(*)} \to D^{(*)}$ and $B_s^{(*)} \to D_s^{(*)}$ modes
- $SU(3)_F$ says that $B^{(*)} \to D^{(*)} \sim B_s^{(*)} \to D_s^{(*)}$

Further inputs:

- Lattice Points for $B_s \to D_s$

[HPQCD 2019]

- Zero-recoil lattice points for $B_s \to D_s^*$

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- The ratios $f_T^{(s)}/f_+^{(s)}$ and f_T/f_+

[M.Atoui, V.Morénas, D. Bečiveric, F. Sanfilippo, '13]

- The ratio $f_0^{(s)}(q^2 = m_\pi^2)/f_0(q^2 = m_\pi^2)$

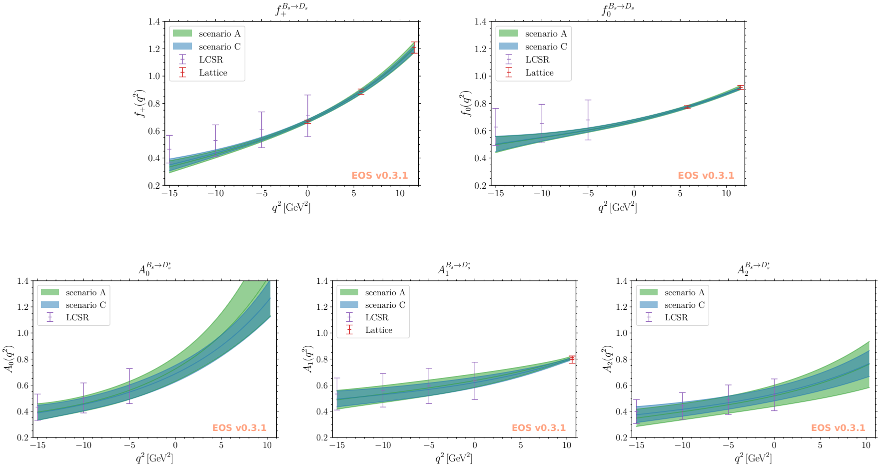
[Fermilab/MILC 2015]

- recast of the QCD sum rules for s quark
- LCSR results for $B_s \to D_s^{(*)}$

[MB, Gubernari, Jung, van Dyk, Eur.Phys.J.C 80 (2020)]

Fit for $B_s \to D_s^{(*)}$

[MB, Gubernari, Jung, van Dyk, Eur.Phys.J.C 80 (2020)]



Predictions

1) Universality ratios

$$R(D) = 0.2989 \pm 0.0032$$
$$R(D^*) = 0.2472 \pm 0.0050$$
$$R(D_s) = 0.2970 \pm 0.0034$$
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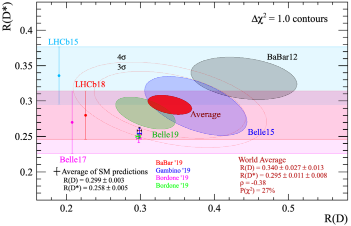

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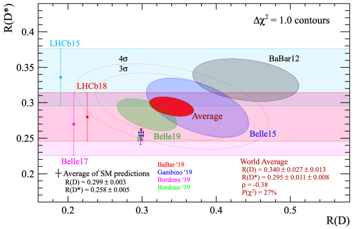

2) V_{cb} extraction

$$V_{cb}|_{BD} = (40.7 \pm 1.1) \times 10^{-3}$$

$$V_{cb}|_{BD*} = (38.8 \pm 1.4) \times 10^{-3}$$

$$V_{cb} = (41.1 \pm 0.5) \times 10^{-3}$$
combination with inclusive
compatibility $1.8\,\sigma$

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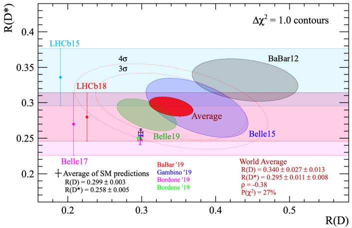

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3) $SU(3)_F$ breaking

From posteria distribution of unitarity bounds: **no evidence** of $SU(3)_F$ symmetry

Summary

- The form factors for $B \to D^{(*)}$ decays are key inputs for many phenomenological application
- The little lattice information regarding $B \to D^*$ form factors requires the use of non-perturbative techniques to parametrise them
- HQET provides an excellent framework which allows to relate form factors for $B^{(*)} \to D^{(*)}$ decays reducing the number of independent form factor
- In our approach
  - We introduce full $1/m_c^2$ corrections
  - We study the optimal order expansion for the form factors
  - We study also the $B_s \to D_s^{(*)}$ case and observe no $SU(3)_F$ breaking
  - We provide interesting predictions for $R_{D^{(*)}}$ and V_{cb}

Appendix

Hadronic Matrix Elements in $B_q \to D_q^{(*)}$ decays

Hadronic decays

- Whenever calculating a hadronic matrix elements we have to deal with non-perturbative effects encoded in form factors
- The method better suited to calculate them is Lattice QCD
- Lattice QCD results in the whole kinematic allowed space are available for the $B_q \to D_q$ mode

  [HPQCD 2015, Fermilab/MILC 2015, FLAG 2016, HPQCD 2019]

- For the $B_q \to D_q^*$ mode, only points at zero recoil are available for a subgroup of the form factors

  [Fermilab/MILC 2014, HPQCD 2017, HPQCD 2019]

More theory inputs needed

HQET in a nutshell

- $b \to c$: the partonic transition involves only heavy quarks
- in the limit $m_{b,c} \to \infty$ but $m_c/m_b = \text{finite}$

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

  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 information 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 (only $J^P = 1^\pm$)

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

- HQET + dispersive bounds + data

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

Open issues:

- Are the expansions used so far enough?
- Is there a way to parametrise form factors without using data?

Our approach

- We expand the FFs using HQET
- We introduce a **consistent** power counting: $\epsilon^2 \sim \frac{\alpha_s}{\pi} \sim \frac{\bar{\Lambda}}{2m_b} \sim \frac{\bar{\Lambda}^2}{4m_c^2}$
  - full $1/m_c^2$ terms **must** be introduced
  - available only partially [Jung, Straub,'18]
  - The IW functions are expanded in the conformal variable z

$$\xi = \xi_0 + \sum \xi^{(n)} z^n$$

  - The order at which we expand leading, subleading and sub-subleading IW functions is determined by comparing different fits
- We use the **full set** of unitary bounds for all the decays $B^{(*)} \to D^{(*)}$

[MB, Jung, van Dyk, Eur. Phys. J. C 80, 74 (2020)]

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- Lattice points for $B \to D$ and

[HPQCD 2015, Fermilab/MILC 2015, FLAG 2016]

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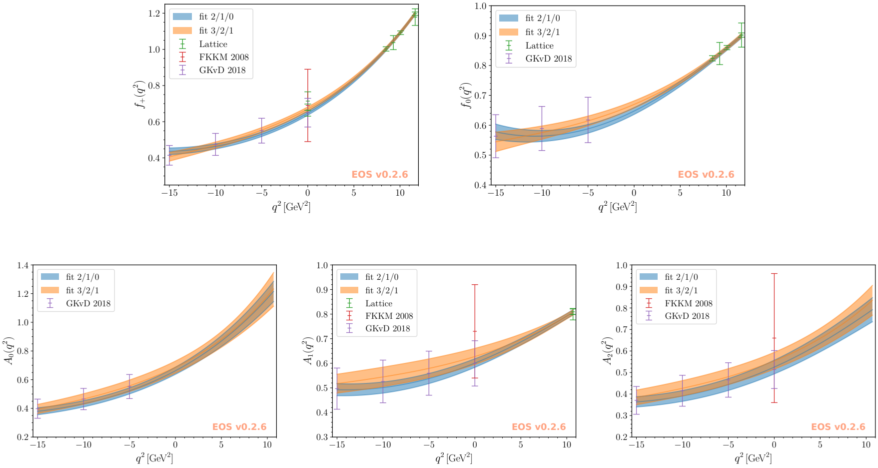

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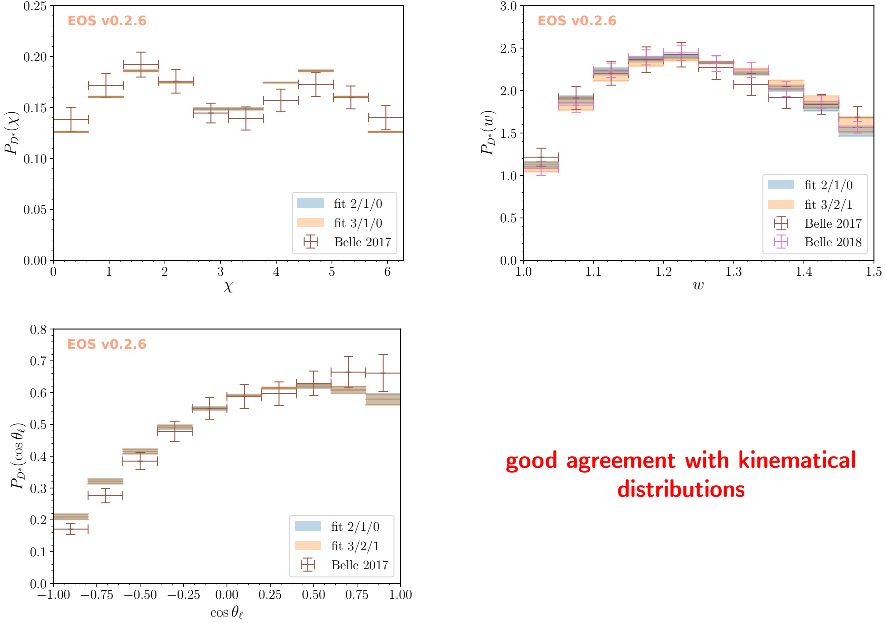

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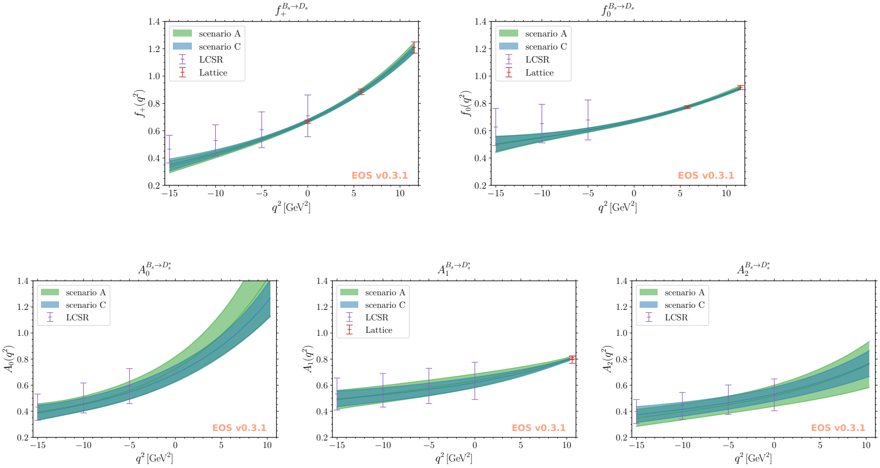
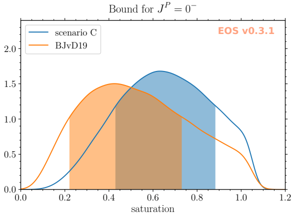
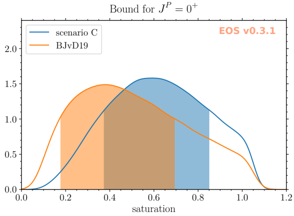
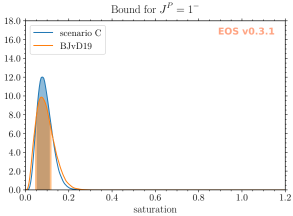
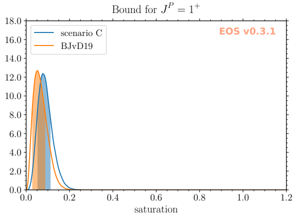


Results: unitary bounds









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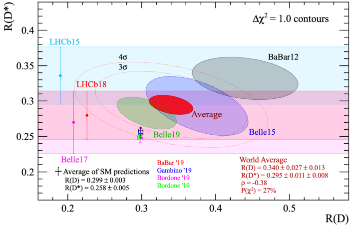


V_{cb} extraction:

$$V_{cb}|_{BD} = (40.7 \pm 1.1) \times 10^{-3} \longleftarrow 1.5\sigma$$

$$V_{cb}|_{BD*} = (38.8 \pm 1.4) \times 10^{-3} \longleftarrow 2\sigma$$

Compatibility with LHCb analysis of $B_s \to D_s^{(*)}$ **[2001.03225]**

- Compatibility with $R^{(*)} = \mathcal{B}(B_s \to D_s^{(*)} \mu\bar{\nu}) / \mathcal{B}(B \to D^{(*)} \mu\bar{\nu})$ and $\mathcal{B}(B_s \to D_s^* \mu\bar{\nu}) / \mathcal{B}(B_s \to D_s \mu\bar{\nu})$ at less than 1σ

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

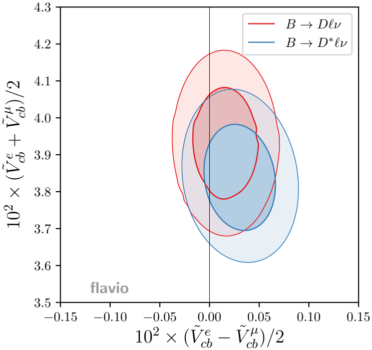
[Jung, Straub 2018]

- 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

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

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

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

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

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

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

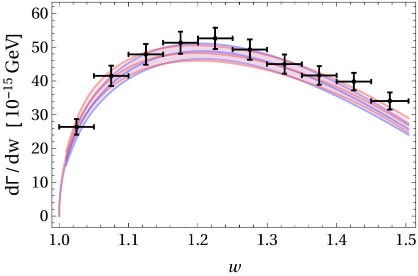
BGL vs CLN

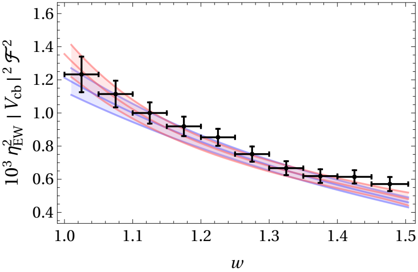
- Both BGL and CLN parametrisation of form factors rely on using unitarity arguments.

[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 $\Lambda_{\textsf{NP}} >> v$: the SM gauge group is not broken up to $\Lambda_{\textsf{NP}}$

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

Scalar solutions

With scalars LQ, we need at least **two** mediators

- Composite scenario: $S_1{+}S_3$ **[D.Marzocca]**
  - Strong dynamics not known
  - B_s mixing + EWPT create tension with $R_{D^{(*)}}$
  - Need to enforce some couplings to be zero to avoid proton decay

- GUT inspired scenarios: $S_3 + R_2$ **[Bečiveríc, Doršner, Fajfer, Faroughy,Košnik,Sumensari]**
  - Predicts interesting LFV signals
  - No explicit realisation so far which avoids proton decay

What is still to be done?

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

- Colourless solution $W' + Z'$: tension with high-p_T searches with $\tau_L \tau_L$ or $b_L b_L$ final states **[Greljo,Isidori,Marzocca,'15]**

- Solutions with right-handed neutrino are motivated and help to ease the tension with $b \to c\tau\nu$ data but they are most likely to be excluded from high-p_T **[Greljo, Camalich,Ruiz-Álvarez,'18]**

It seems like there is not much space left...

What are we looking for?

...but data can help us!

If the anomalies are trues, NP **must** appear somewhere else.

A full dedicated flavour physics program run by LHCb, Belle II but also experiments like NA62 is needed to

- determine the flavour structure of the NP sector;
- different correlations among low energy observable can help to distinguish the possible models.

Only with such programs will we be able to determine what type of NP is realised in nature.

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

Hadronic Matrix Elements

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

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

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