Status and prospects of form factors for charged-current decays

Marzia Bordone

UNIVERSITÀ
DEGLI STUDI
DI TORINO

LHCb Implications

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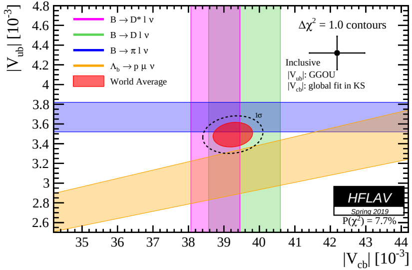
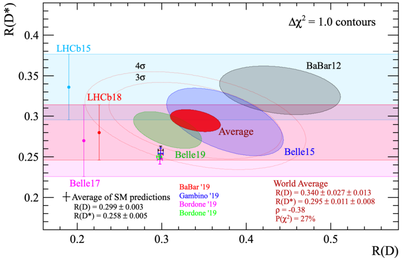
The importance of semileptonic decays

1) Measurement of CKM elements V_{xb} from exclusive and inclusive channels

- test of the CKM unitarity
- important inputs for several observables



2) Key decays in the search for NP



From parton to hadrons

The scale characterising hadron dynamics is Λ_{QCD}

- Non perturbative techniques are needed

$$\langle H_{(u,c)}|J_\mu|H_b\rangle = \sum_i S^i_\mu \mathcal{F}_i$$

$\mathcal{F}_i$: is a form factor, a scalar function encoding the non perturbative dynamics

- Lattice QCD [Christine's Davies talk]
- Sum Rules, HQE, etc.

Usually uncertainties are sizeable....

Focus on $B \to D^{(*)}$ form factors

$B \to D^{(*)}$ form factors

- 7 (SM) + 3 (NP) form factors
- Lattice computation for $q^2 \neq q^2_{\text{max}}$ only for $B \to D$
- Calculation usually give only a few points
  - q^2 dependence must be inferred

BGL+HQE: conformal variable z

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

- $t_+ = (m_B + m_{D^{(*)}})$ pair production threshold
- $t_0 < t_+$ free parameter that can be used to minimise $|z_{\text{max}}|$
- $|z| \ll 1$, in the $B \to D$ case $|z| < 0.06$

BGL parametrisation

[Boyd, Grinsten, Lebed, '95]

- Model independent parametrisation of form factors
- Based on analyticity of the form factors
- Expansion of FFs using the conformal variable z

$$F_i = \frac{1}{P_i(z)\phi_i(z)} \sum_{k=0}^{n_i} a_k^i z^k$$

P_i: Blaschke factors, ϕ_i outer functions

- Weak unitarity constraints

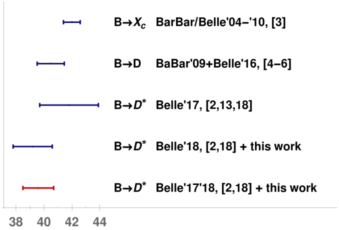
$$\sum_k (a_k)^2 < 1$$

- Large number of free parameters

The BGL fit

[Bernlochner et al, Nandi et al,..]
[Gambino, Jung, Schacht, '19]

- Belle data from 2017 and 2018 are available
- Lattice data (when available)
- LCSR results at $q^2 = 0$
- Expansion up to z^2: better control over the uncertainties on the BGL parameters



$$V_{cb}^{D^*} = (39.6^{+1.1}_{-1.0}) \times 10^{-3}$$
$$V_{cb}^{\text{incl}} = (42.0 \pm 0.64) \times 10^{-3} \quad \Rightarrow 1.9\,\sigma$$
$$R_{D^*} = 0.254^{+0.007}_{-0.006}$$

The HQE parametrisation

- Expansion of QCD Lagrangian in $1/m_{b,c} + \alpha_s$ corrections

  [Caprini, Lellouch, Neubert, '97]

- In the limit $m_{b,c} \to \infty$: all $B \to D^{(*)}$ form factors are given by a **single** Isgur-Wise function

- at higher orders the form factors are still related $\Rightarrow$ **reduction** of free parameters

Problem: contradiction with lattice data!

- HQE provides precise predictions for some of the form factors at zero-recoil

- $1/m_c^2$ corrections **have to be systematically included**

  [Jung, Straub, '18, MB, M.Jung, D.van Dyk, '19]

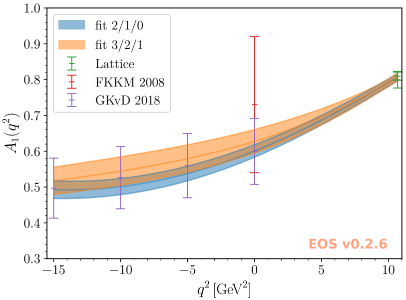
  - well motivated also since $\alpha_s/\pi \sim 1/m_b \sim 1/m_c^2$

The HQE results

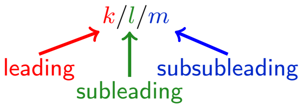
- Unitarity bounds
- Lattice for $B_q^{(*)} \to D_q^{(*)}$
- LCSR for all form factors (except tensor)

[Gubernari, Kokulu, van Dyk, '18
MB, N. Gubernari, M.Jung, D.van Dyk, '19]

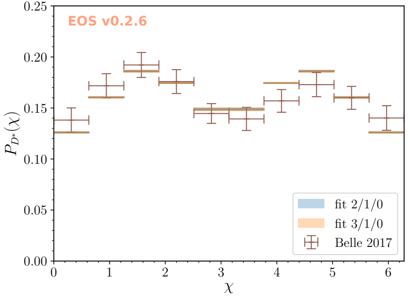
- Consistent expansion to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$
- Breaking of $SU(3)_F$ for light and strange spectators

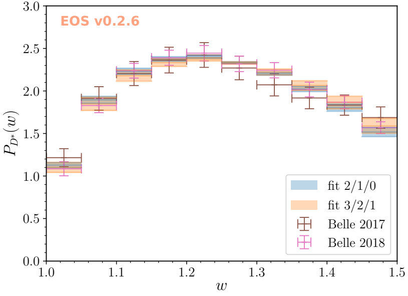


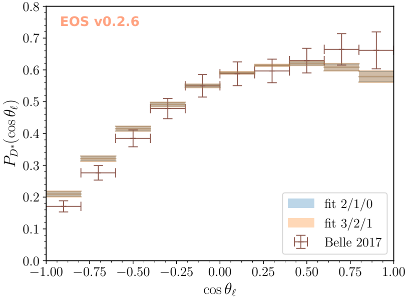
- Fit to theory inputs only
- Expansion in z up to order



Challenging data



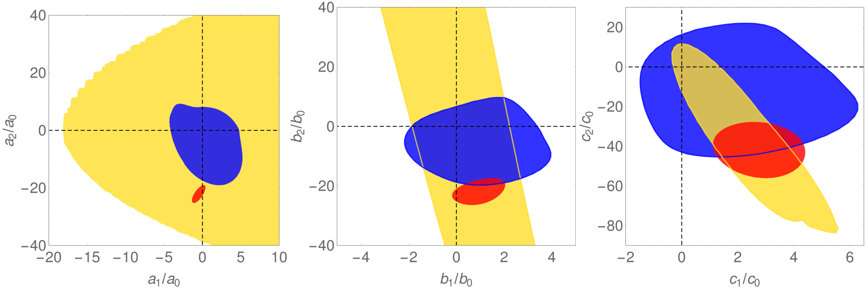




- Both 2/1/0 and 3/2/1 fit well describe data statistically
- Is there any difference between the two fits?

Fit stability

- BGL fit to Belle 2017 and 2018 data (yellow)
- HQE fit 2/1/0 (red)
- HQE fit 3/2/1 (blue)



- compatibily of HQE fit with data driven one
- 2/1/0 underestimates massively uncertainties

$3/2/1$ is our nominal fit

Phenomenological results

- V_{cb} extraction

$$V_{cb}^{\textsf{average}} = (41.1 \pm 0.5) \times 10^{-3}$$

compatibility of 1.8σ between inclusive and exclusive

- Universality ratios

$$R_{D^*} = 0.2472 \pm 0.0050$$

towards the combined 4σ discrepancy

- We observe no $SU(3)_F$ breaking

- Good compatibility with LHCb $\bar{B}_s \to D_s^{(*)}$ analysis in 2001.03225

- Very interesting implications for non-leptonic $\bar{B}_{(s)}$ decays [2007.10338]

Wishlist: Experimental

- $B_s \to K_S$ and $B_s \to K^*$ [Gubernari, van Dyk, 1703.04765]
- $B \to \rho$: is the pion stable enough?
  - $B \to \rho$ FFs from LCSR [1811.00983]
  - $B \to \pi\pi$ FFs from LCSR [1511.02509,1701.01633]
- $B \to D^{**}$
  - HQE expansion [1711.03110]
  - LCSR, on going [Gubernari, Khodjamirian, Mandal, Mannel]
- $B_c \to D$ FFs: not easy to estimate... [Peset, van Dyk]

Wishlist: Theory

- $B \to D^{**}$: any type of data
- $\Lambda_b \to \Lambda_c$: measurement of the ratio (τ/μ) hadronic forward-backward asymmetry
  - large sensitivity to NP [1907.12554]
- $\Lambda_b \to \Lambda_c^*$: LHCb measurement needed to fix the hadronic parameters [1801.08367]
- Any update of $R(H_c)$
- We need data in terms of FFs independent distributions

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Appendix

Inputs

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- Lattice points for $B \to D$ and $B_s \to D_s$

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

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

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

- 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]

- QCD sum rules for subleading Isgur-Wise Functions
  - update of the results for light quarks and consistent treatment of uncertainties
  - recast of the sum rules for s quark

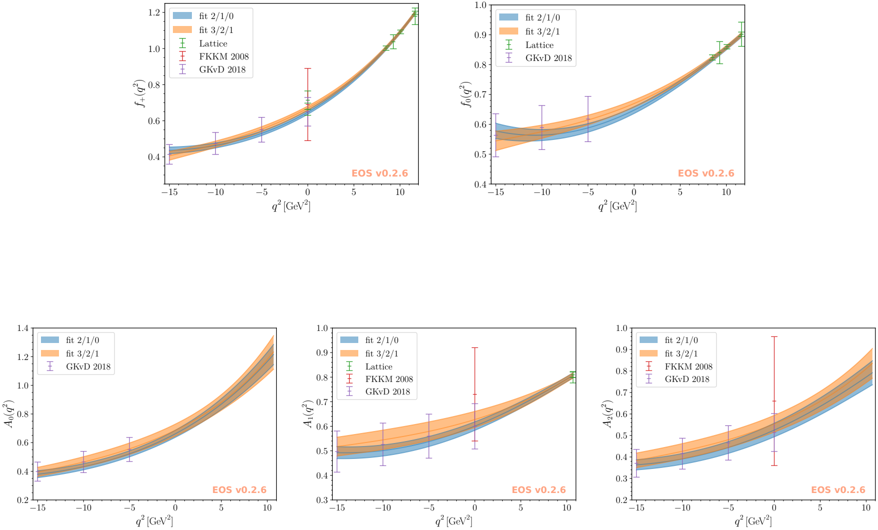
  [MB, Gubernari, Jung, van Dyk, 2019]

- Introduce new LCSR results

  [Gubernari, Kokulu, van Dyk, 2018 MB, Gubernari, Jung, van Dyk, 2019]

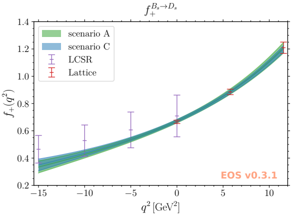
Fit results

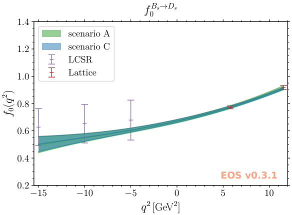
[MB, Jung, van Dyk, Eur. Phys. J. C 80, 74 (2020)]

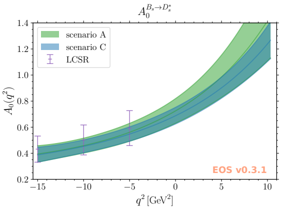


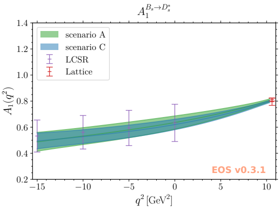
Fit for $B_s \to D_s^{(*)}$

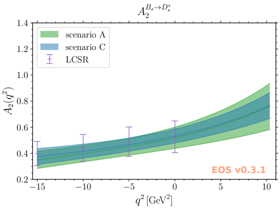
[MB, Gubernari, Jung, van Dyk, 1912.09335]



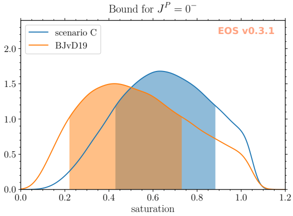


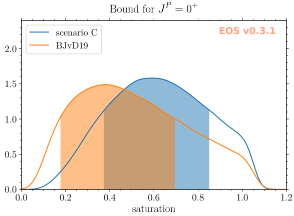


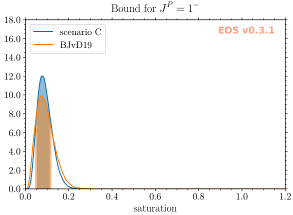


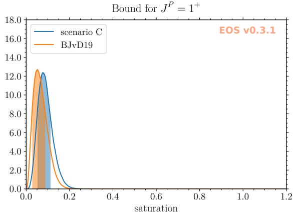


Results: unitary bounds





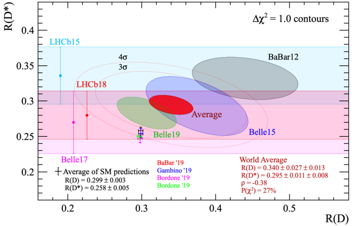




Predictions

Universality Ratios:

$$R(D) = 0.2989 \pm 0.0032$$
$$R(D^*) = 0.2472 \pm 0.0050$$
$$R(D_s) = 0.2970 \pm 0.0034$$
$$R(D_s^*) = 0.2450 \pm 0.0082$$



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

V_{cb} and NP

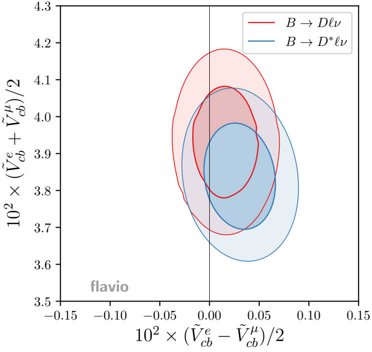
[Jung, Straub 2018]

- 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

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



$$\frac{1}{2}(\tilde{V}_{cb}^{e} + \tilde{V}_{cb}^{\mu}) = (3.87 \pm 0.09)\%$$
$$\frac{1}{2}(\tilde{V}_{cb}^{e} + \tilde{V}_{cb}^{\mu}) = (0.022 \pm 0.023)\%$$