Standard Model Predictions and New Physics in $b \to c$ transitions

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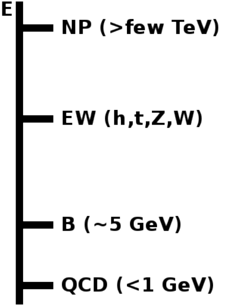
$b \to c$ transitions in and beyond the SM

$b \to c$ transitions...

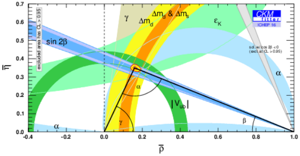
- ...are an example of flavour-changing transitions
- ...proceed in the SM via the weak interaction
  ➥ access to a fundamental SM parameter, V_{cb}
- ...dominate lifetimes of singly-heavy groundstate B hadrons
- ...exhibit important hierarchies:



- Employ $\Lambda_{\mathrm{EW}} \gg m_{b,c}$:
  ➥ Effective Theory with local 4-fermion operators
  ➥ Two classes, semileptonic and nonleptonic
- Employ $m_b \gtrsim m_c \gg \Lambda_{\mathrm{QCD}}$:
  Heavy-quark expansion, tool for matrix elements
- Employ $\Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}}$:
  ➥ Effective Theories (SMEFT, HEFT)
  ➥ Model-independent NP parametrizations

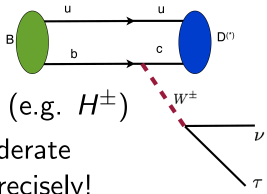
Tensions in $b \to c\tau\nu$, $b \to c\ell\nu$ (V_{cb} puzzle) and $B_{d,s} \to D_{d,s}^{(*)}(\pi, K)$

Importance of (semi-)leptonic hadron decays



In the Standard Model:

- Tree-level, $\sim |V_{ij}|^2 G_F^2\, \mathrm{FF}^2$
- Determination of $|V_{ij}|$ (6(+1)/9)



Beyond the Standard Model:

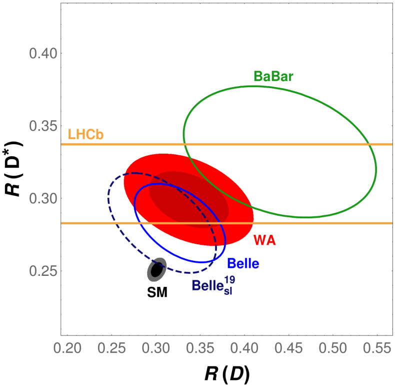
- Leptonic decays $\sim m_l^2$
  - ➥ large relative NP influence possible (e.g. $H^\pm$)
- NP in semi-leptonic decays small/moderate
  - ➥ Need to understand the SM very precisely!
    For instance isospin breaking in $\Upsilon(4S) \to B\bar{B}$ [MJ'15]

Key advantages:

- Large rates
- Minimal hadronic input ⇒ systematically improvable
- Differential distributions ⇒ large set of observables

Lepton-non-Universality in $b \to c\tau\nu$

$$R(X) \equiv \frac{\mathrm{Br}(B \to X\tau\nu)}{\mathrm{Br}(B \to X\ell\nu)}, \quad \hat{R}(X) \equiv \frac{R(X)}{R(X)|_{\mathrm{SM}}}$$



contours: 68% CL
filled: 95(68)% CL

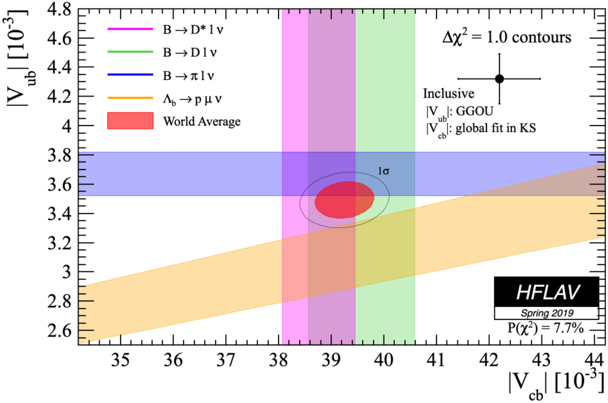
- $R(D^{(*)})$: BaBar, Belle, LHCb
  - average $\sim 4\sigma$ from SM
- τ-polarization ($\tau \to$ had) [1608.06391]
- $B_c \to J/\psi\tau\nu$ [1711.05623] : huge
- Differential rates from Belle, BaBar
- Total width of B_c
- $b \to X_c\tau\nu$ by LEP
- D^* polarization (Belle)
- Moriond'19: Belle update
  - Reduced significance (partly $B \to D^*\ell\nu$)

Note: only 1 result $\geq 3\sigma$ from SM

Puzzling V_{cb} results

The V_{cb} puzzle has been around for 20+ years...

- $\sim 3\sigma$ between exclusive (mostly $B \to D^* \ell\nu$) and inclusive V_{cb}
- Inclusive determination: includes $\mathcal{O}(1/m_b^3, \alpha_s/m_b^2, \alpha_s^2)$
  - ➥ Excellent theoretical control, $|V_{cb}| = 42.00 \pm 0.64$
- Exclusive determinations: $B \to D^{(*)}\ell\nu$, using CLN (fixed!)
  - ➥ CLN: HQE @ $\mathcal{O}(1/m_{c,b}, \alpha_s)$ + slope-curvature relation in ξ



Recent developments

- Unfolded differential measurements made available by Belle
  - ➥ Different parametrizations possible
  - ➥ Important step for phenomenology!
- Lattice calculations for $B \to D$ FFs at non-zero recoil

➥ BGL $B \to D\ell\nu$ analysis: $|V_{cb}| \sim |V_{cb}^{\rm incl.}|$, CLN fit bad [Bigi+'16]
  - ➥ but HQE analysis w/ partial $1/m_c^2$ ok [Bernlochner+'17,MJ/Straub'18]

- Belle 2017 $B \to D^*\ell\nu$ data: large difference between CLN and BGL [Bigi+,Grinstein+,Jaiswal+'17] , $|V_{cb}^{\rm BGL}| \sim |V_{cb}^{\rm incl.}|$
- Belle 2018: no parametrization-dependence seen, $|V_{cb}|$ lower

➥ Intense discussion, no clear picture at first

First thing to do when noticing inconsistencies: Check SM predictions!

➥ For semileptonic decays, that means mostly form factors

Form Factor Basics

Form Factors (FFs) parametrize fundamental mismatch:

Theory (e.g. SM) for partons (quarks)
vs.
Experiment with hadrons

$$\left\langle D_q^{(*)}(p')|\bar{c}\gamma^\mu b|\bar{B}_q(p)\right\rangle = (p+p')^\mu f_+^q(q^2) + (p-p')^\mu f_-^q(q^2)\,,\; q^2 = (p-p')^2$$

Most general matrix element parametrization, given symmetries:
Lorentz symmetry plus P- and T-symmetry of QCD
$f_\pm(q^2)$: scalar functions of one kinematic variable

How to obtain these functions?

- Calculable w/ non-perturbative methods (Lattice, LCSR,...)
  Precision?
- Measurable e.g. in semileptonic transitions
  Normalization? Suppressed FFs? NP?

q^2 dependence

- q^2 range can be large, e.g. $q^2 \in [0, 12]\ \mathrm{GeV}^2$ in $B \to D$
- Calculations give usually one or few points
- ➥ Knowledge of functional dependence on q^2 cruical
- This is where discussions start...

Experiments should give information independent of this choice!

In the following: discuss BGL and HQE ($\to$ CLN) parametrizations

q^2 dependence usually rewritten via conformal transformation:

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

$t_+ = (M_{B_q} + M_{D_q^{(*)}})^2$: pair-production threshold

$t_0 < t_+$: free parameter for which $z(t_0, t_0) = 0$

Usually $|z| \ll 1$, e.g. $|z| \leq 0.06$ for semileptonic $B \to D$ decays

➥ Good expansion parameter

The BGL parametrization [Boyd/Grinstein/Lebed, 90's]

FFs are parametrized by a few coefficients the following way:

1. Consider analytical structure, make poles and cuts explicit
2. Without poles or cuts, the rest can be Taylor-expanded in z
3. Apply QCD properties (unitarity, crossing symmetry)
   ➥ dispersion relation
4. Calculate partonic part perturbatively (+condensates)

Result:

$$F(t) = \frac{1}{P(t)\phi(t)} \sum_{n=0}^{\infty} a_n [z(t, t_0)]^n \,.$$

- a_n: real coefficients, the only unknowns
- $P(t)$: Blaschke factor(s), information on poles below t_+
- $\phi(t)$: Outer function, chosen such that $\sum_{n=0}^{\infty} a_n^2 \leq 1$

➥ Series in z with bounded coefficients (each $|a_n| \leq 1$)!

➥ Uncertainty related to truncation is calculable!

$V_{cb} + R(D^*)$ w/ data + lattice + unitarity [Gambino/MJ/Schacht'19]

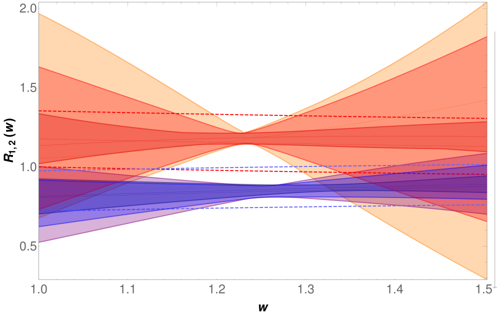
(see also [Fajfer+,Nierste+,Bernlochner+,Bigi+,Grinstein+,Nandi+...])
Recent untagged analysis by Belle with 4 1D distributions [1809.03290]

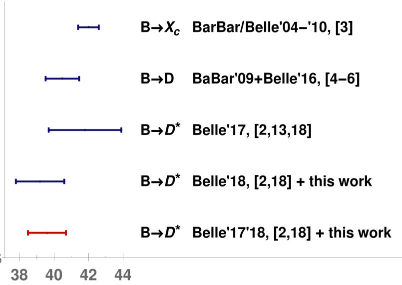
➥ *"Tension with the (V_{cb}) value from the inclusive approach remains"*

Analysis of 2017+2018 Belle data with BGL form factors:

- Datasets roughly compatible
- d'Agostini bias + syst. important
- All FFs to z^2 to include uncertainties
- 2018: no parametrization dependence

$$|V_{cb}^{D^*}| = 39.6^{+1.1}_{-1.0} \times 10^{-3}$$
$$R(D^*) = 0.254^{+0.007}_{-0.006}$$





HQE parametrization

HQE parametrization uses additional information compared to BGL

➥ Heavy-Quark Expansion (HQE)

- $m_{b,c} \to \infty$: all $B \to D^{(*)}$ FFs given by 1 Isgur-Wise function
- Systematic expansion in $1/m_{b,c}$ and α_s
- Higher orders in $1/m_{b,c}$: FFs remain related
  ➥ Parameter reduction, necessary for NP analyses!

CLN parametrization [Caprini+'97] :
HQE to order $1/m_{b,c}, \alpha_s$ plus (approx.) constraints from unitarity
[Bernlochner/Ligeti/Papucci/Robinson'17] : identical approach, updated and consistent treatment of correlations

Problem: Contradicts Lattice QCD (both in $B \to D$ and $B \to D^*$)
Dealt with by varying calculable (@$1/m_{b,c}$) parameters, e.g. $h_{A_1}(1)$

➥ Not a systematic expansion in $1/m_{b,c}$ anymore!

➥ Related uncertainty remains $\mathcal{O}[\Lambda^2/(2m_c)^2] \sim 5\%$, insufficient

Solution: Include systematically $1/m_c^2$ corrections
[Bordone/MJ/vDyk'19,Bordone/Gubernari/MJ/vDyk'20] ,using [Falk/Neubert'92]

Theory determination of $b \to c$ Form Factors

SM: BGL fit to data + FF normalization $\to |V_{cb}|$

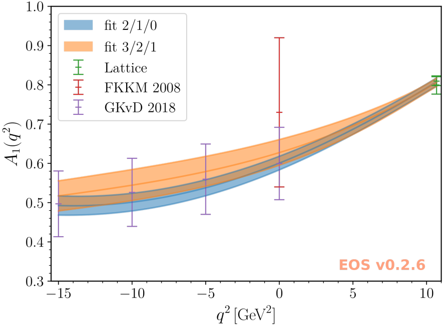
NP: can affect the q^2-dependence, introduces additional FFs

➥ To determine general NP, FF shapes needed from theory

In [MJ/Straub'18,Bordone/MJ/vDyk'19] , we use all available theory input:

- Unitarity bounds (using results from [BGL,Bigi/Gambino(/Schacht)'16'17])
- LQCD for $f_{+,0}(q^2)$ $(B \to D)$, $h_{A_1}(q^2_{\max})$ $(B \to D^*)$ [HPQCD'15,'17,Fermilab/MILC'14,'15]
- LCSR for all FFs (but f_T) [Gubernari/Kokulu/vDyk'18]
- Consistent HQET expansion [Bernlocher+] to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$
  ➥ improved description

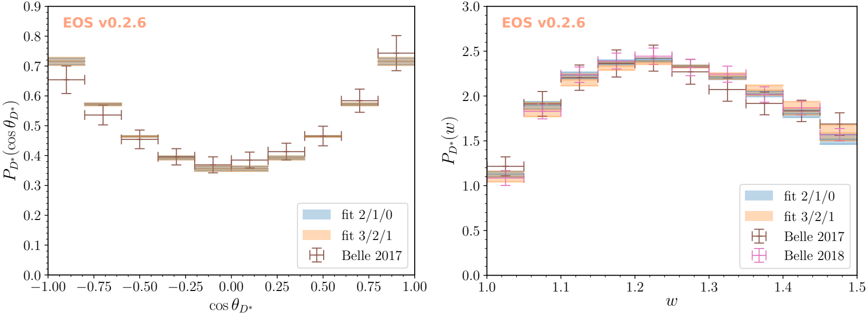
FFs under control;
$R(D^*) = 0.247(6)$
[Bordone/MJ/vDyk'19]



Robustness of the HQE expansion up to $1/m_c^2$

[Bordone/MJ/vDyk'19]

Testing FFs by comparing to data and fits in BGL parametrization:



- Fits 3/2/1 and 2/1/0 are theory-only fits(!)
- $k/l/m$ denotes orders in z at $\mathcal{O}(1, 1/m_c, 1/m_c^2)$
- w-distribution yields information on FF shape $\rightarrow V_{cb}$
- Angular distributions more strongly constrained by theory, only

➥ Predicted shapes perfectly confirmed by $B \rightarrow D^{(*)}\ell\nu$ data

➥ V_{cb} from Belle'17 compatible between HQE and BGL!

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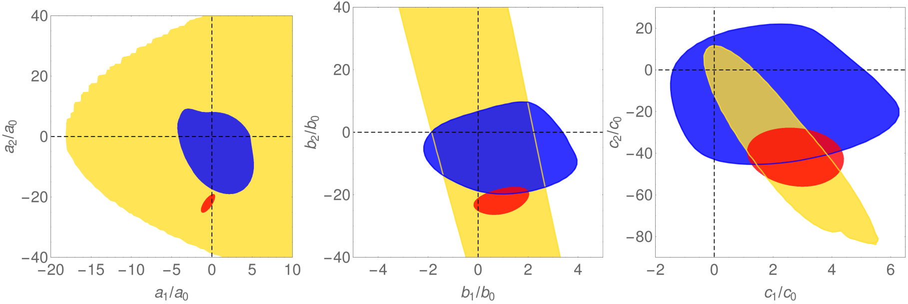


- $B \to D^*$ BGL coefficient ratios from:
  1. Data (Belle'17+'18) + weak unitarity (yellow)
  2. HQE theory fit 2/1/0 (red)
  3. HQE theory fit 3/2/1 (blue)

➥ Again compatibility of theory with data

➥ 2/1/0 underestimates the uncertainties massively

➥ For b_i, c_i ($\to f, \mathcal{F}_1$) data and theory complementary

Including $\bar{B}_s \to D_s^{(*)}$ Form Factors [Bordone/Gubernari/MJ/vDyk'20]

Dispersion relation *sums* over hadronic intermediate states

- Includes $B_s D_s^{(*)}$, included via SU(3) + conservative breaking
- Explicit treatment can improve also $\bar{B} \to D^{(*)}\ell\nu$

Experimental progress in $\bar{B}_s \to D_s^{(*)}\ell\nu$:
2 new LHCb measurements [2001.03225, 2003.08453]

Improved theory determinations required, especially for NP

We extend our $1/m_c^2$ analysis by including:

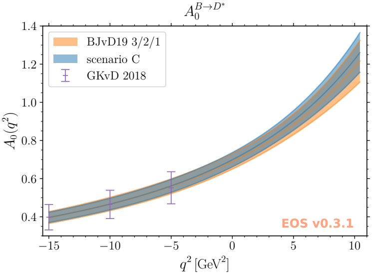
- Available lattice data:
  (2 $\bar{B}_s \to D_s$ FFs (q^2 dependent), 1 $\bar{B}_s \to D^*$ FF (only $q^2_{\max}$))
- Adaptation of existing QCDSR results [Ligeti/Neubert/Nir'93'94] , including SU(3) breaking
- New LCSR results extending [Gubernari+'18] to B_s, including SU(3) breaking

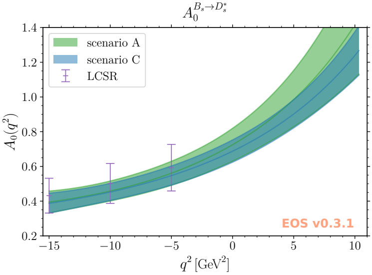
- Fully correlated fit to $\bar{B} \to D^{(*)}, \bar{B}_s \to D_s^{(*)}$ FFs

Including $\bar{B}_s \to D_s^{(*)}$ Form Factors, Results

We observe the following:

- Theory constraints fitted consistently in an HQE framework
- $\mathcal{O}(1/m_c^2)$ power corrections have $\mathcal{O}(1)$ coefficients
- No indication of sizable SU(3) breaking
- Slight influence of strengthened unitarity bounds
- Improved determination of $\bar{B}_s \to D_s^{(*)}$ FFs





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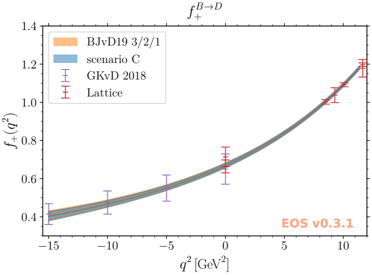

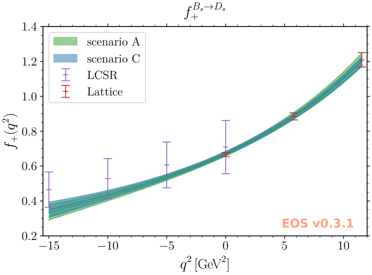

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Theory-only predictions:

$$R(D) = 0.2989(32) \qquad R(D^*) = 0.2472(50)$$
$$R(D_s) = 0.2970(34) \qquad R(D_s^*) = 0.2450(82)$$

Theory+Experiment (Belle'17) predictions:

$$R(D) = 0.2981(29) \qquad R(D^*) = 0.2504(26)$$
$$R(D_s) = 0.2971(34) \qquad R(D_s^*) = 0.2472(77)$$

BSM fits in $b \to c\ell\nu$: Experimental analyses used

Decay	Observable	Experiment	Comment	Year
$\boldsymbol{B \to D(e,\mu)\nu}$	BR	BaBar	global fit	2008
$B \to D\ell\nu$	$\frac{d\Gamma}{dw}$	BaBar	hadronic tag	2009
$\boldsymbol{B \to D(e,\mu)\nu}$	$\frac{d\Gamma}{dw}$	Belle	hadronic tag	2015
$\boldsymbol{B \to D^*(e,\mu)\nu}$	BR	BaBar	global fit	2008
$B \to D^*\ell\nu$	BR	BaBar	hadronic tag	2007
$B \to D^*\ell\nu$	BR	BaBar	untagged B^0	2007
$B \to D^*\ell\nu$	BR	BaBar	untagged $B^\pm$	2007
$\boldsymbol{B \to D^*(e,\mu)\nu}$	$\frac{d\Gamma_{L,T}}{dw}$	Belle	untagged	2010
$B \to D^*\ell\nu$	$\frac{d\Gamma}{d(w,\cos\theta_V,\cos\theta_l,\phi)}$	Belle	hadronic tag	2017

Different categories of data:

- Only total rates vs. differential distributions
- e,μ-averaged vs. individual measurements
- Correlation matrices given or not

➥ Sometimes presentation prevents use in non-universal scenarios ☹

➥ Recent Belle analyses (mostly) exemplary ☺

BSM fits in $b \to c\ell\nu$: $\mathcal{O}_{V_L}$ [MJ/Straub'18]

As a crosscheck, produce SM values (using data from HEPdata):

$V_{cb}^{B\to D} = (39.6 \pm 0.9)10^{-3}$ $\quad$ $V_{cb}^{B\to D^*} = (39.0 \pm 0.7)10^{-3}$

➥ low compared to BGL analyses, compatible with recent results

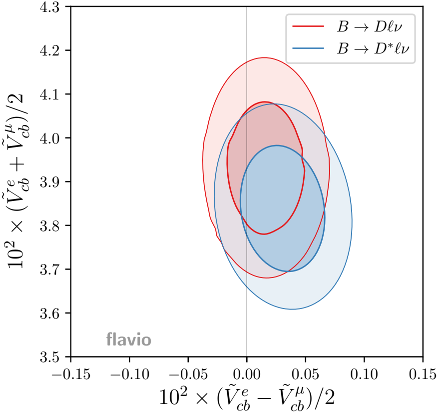
NP in $\mathcal{O}_{V_L}^{\ell\ell'}$: can be absorbed via $\tilde{V}_{cb}^{\ell} = V_{cb}\left[|1+C_{V_L}^{\ell}|^2 + \sum_{\ell'\neq\ell}|C_{V_L}^{\ell\ell'}|^2\right]^{1/2}$

Only subset of data usable

$B \to D, D^*$ in agreement

No sign of LFNU

➥ constrained to be $\lesssim \% \times V_{cb}$



In the following:

- e and μ analyzed separately
  ➥ Usable in different contexts
- Full FF constraints used

Plots created with **flavio**

+ independently double-checked

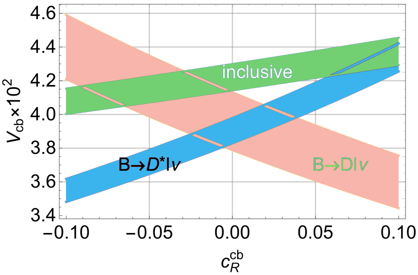
➥ Open source, adaptable

Right-handed vector currents [MJ/Straub'18]

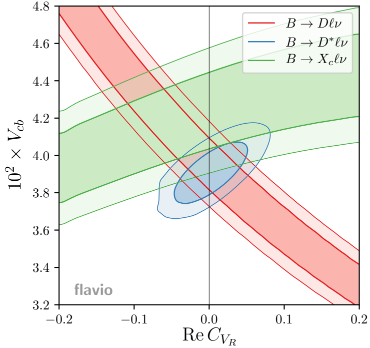
Usual suspect for tension inclusive vs. exclusive [e.g. Voloshin'97]

SMEFT: $C_{V_R}^{\ell\ell'}$ is lepton-flavour-universal [Cirigliano+'10,Catà/MJ'15]

- All available data can be used in SMEFT context
- Violation could signal non-linear realization of EWSB [Catà/MJ'15]



[Plot: updated from Crivellin/Pokorski'14]



Impact of differential distributions:

V_{cb} and C_{V_R} can be determined individually in $B\to D^*$

- Tension smaller, but is not improved by C_{V_R}
- C_{V_R} in SMEFT cannot explain $b\to c\tau\nu$ data

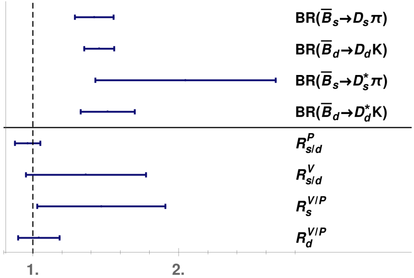
A puzzle in non-leptonic $b \to c$ transitions

[Bordone/Gubernari/Huber/MJ/vDyk'20]

FFs also of central importance in non-leptonic decays:

- Complicated in general, $B \to M_1 M_2$ dynamics
- Simplest cases: $\bar{B}_d \to D_d^{(*)} \bar{K}$ and $\bar{B}_s \to D_s^{(*)} \pi$ (5 diff. quarks)
  - Colour-allowed tree, $1/m_b^0 @ \mathcal{O}(\alpha_s^2)$ [Huber+'16] , factorizes at $1/m_b$
  - Amplitudes dominantly $\sim \bar{B}_q \to D_q^{(*)}$ FFs
  - Used to determine f_s/f_d at hadron colliders [Fleischer+'11]

Prediction/Measurement



Updated and extended calculation: tension of 4.4σ w.r.t. exp.!

Interpretation

- Large effect, $\sim -30\%$ for BRs
- Ratios of branching ratios ok
- Our estimate of $\mathcal{O}(1/m_b)$ contributions could be wrong
  - Requires factor of 500, effectively $\mathcal{O}(1/m_b) \to \mathcal{O}(1)$
- Experimental data consistent (few absolute BRs measured)
  - large BR, simple to measure
- QCDf uncertainty $\mathcal{O}(1/m_b^2, \alpha_s^3)$
  - Much smaller than the observed effect
- NP? $\Delta_P \sim \Delta_V \sim -20\%$ possible
  - Surprising, affects e.g. lifetimes
  - Not easy to avoid collider constraints [Iguro/Kitahara'20]

Whatever the solution,
we will learn something important!

Conclusions

$b \to c$ transitions remain an exciting topic to study

- Several tensions to understand
- Focus here was mostly on FF determinations
  - For BSM analyses, theory determination of FFs required!
  - Previous assumptions ($\to$ CLN) contradicted by lattice data
    - First analysis at $1/m_c^2$ provides all FFs
    - Combines unitarity, lattice, LCSR, QCDSR
    - V_{cb} puzzle much reduced, $R(D^*)$ slightly lower
  - Conservative uncertainty estimates important
    - Higher-order contributions have to be accounted for
  - $b \to c\ell\nu$: strong constraints, qualitative progress for V_R
  - New discrepancy in non-leptonic decays
    - Requires significant revision of our understanding
    - BSM physics possible explanation

Exciting times ahead in $b \to c$ transitions!