# Precision analyses of $b \to c$ transitions

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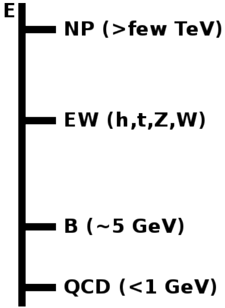
# $b \to c$ transitions in and beyond the SM

$b \to c$ 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:



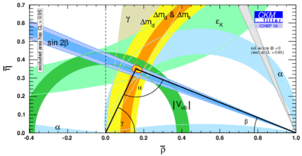

- Employ $\Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}}$:
  - ➥ Effective Theories (SMEFT, HEFT)
  - ➥ Model-independent NP parametrizations
- Employ $\Lambda_{\mathrm{EW}} \gg m_{b,c}$:
  - ➥ Effective Theory with local 4-fermion operators
  - ➥ Two classes, semileptonic and nonleptonic
- Employ $m_b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

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

# Importance of (semi-)leptonic hadron decays

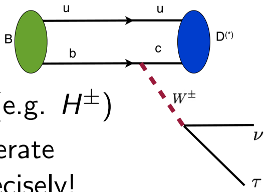
In the Standard Model:

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




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!



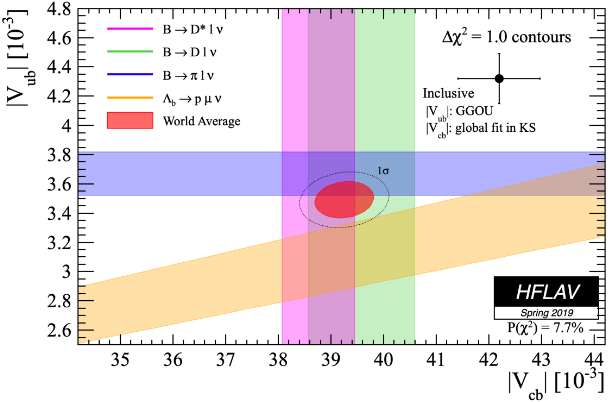

Key advantages:

- Large rates
- Minimal hadronic input $\Rightarrow$ systematically improvable
- Differential distributions $\Rightarrow$ large set of observables

# Puzzling $V_{cb}$ results

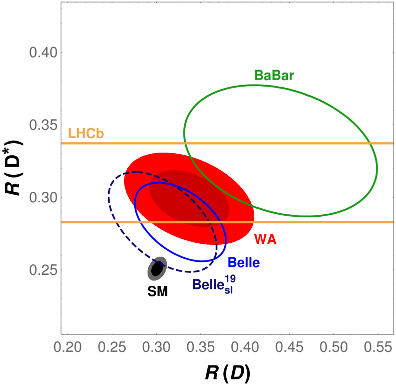
The $V_{cb}$ puzzle has been around for 20+ years...

- $\sim 3\sigma$ between exclusive (mostly $B \to D^* \ell \nu$) and inclusive $V_{cb}$
- Inclusive determination: includes $\mathcal{O}(1/m_b^3, \alpha_s/m_b^2, \alpha_s^3)$
  - ➡ Excellent theoretical control, $|V_{cb}| = (42.2 \pm 0.5)10^{-3}$ [Bordone+'21,Fael+'20,'21]
- Exclusive determinations: $B \to D^{(*)} \ell \nu$, using CLN ($\to$ later)



# 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 $\sim 3 - 4\sigma$ from SM

More flavour $b \to c\tau\nu$ observables:

- $\tau$-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)

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

# Form factors: 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
$f_\pm(q^2)$: real, 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?

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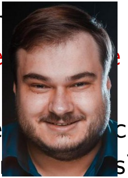

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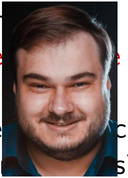


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# $q^2$ dependence

- $q^2$ 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...

**Give as much information as possible 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]

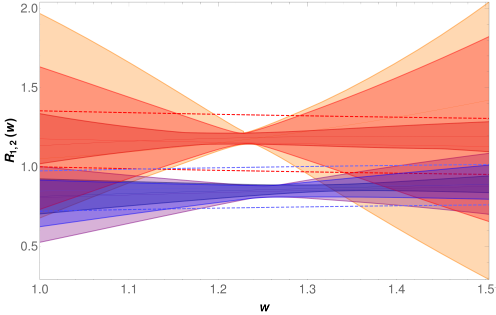
Recent untagged analysis by Belle with 4 1D distributions [1809.03290]

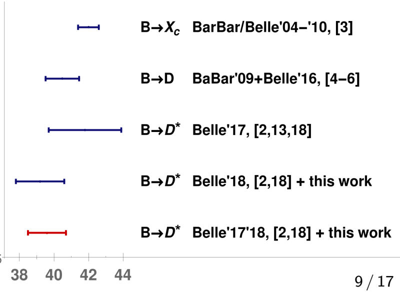
➥ *"Tension with the ($V_{cb}$) value from the inclusive approach remains"*

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
  ➥ 50% increased 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 $\alpha_s$
- 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 $\to |V_{cb}|$

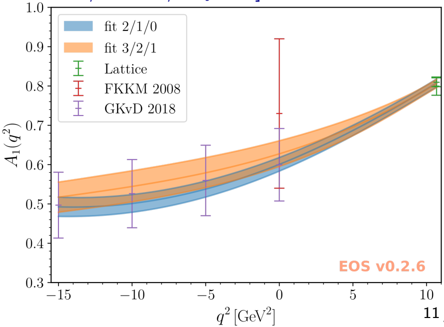
NP: can affect the $q^2$-dependence, introduces additional FFs

➥ To determine general NP, FF shapes needed from theory

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

- Unitarity bounds (using results from [CLN, BGL] )
  - ➥ non-trivial $1/m$ vs. $z$ expansions
- 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 (mod $f_T$) [Gubernari/Kokulu/vDyk'18]
- QCDSR results for $1/m$ IW functions [Ligeti+'92'93]
- HQET expansion to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$

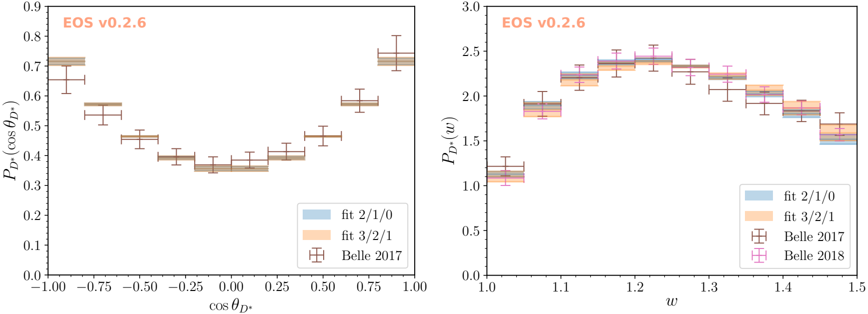
FFs under control;
$R(D^*) = 0.247(6)$
[Bordone/MJ/vDyk'19]



# 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 $\to V_{cb}$
- Angular distributions more strongly constrained by theory, only

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

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

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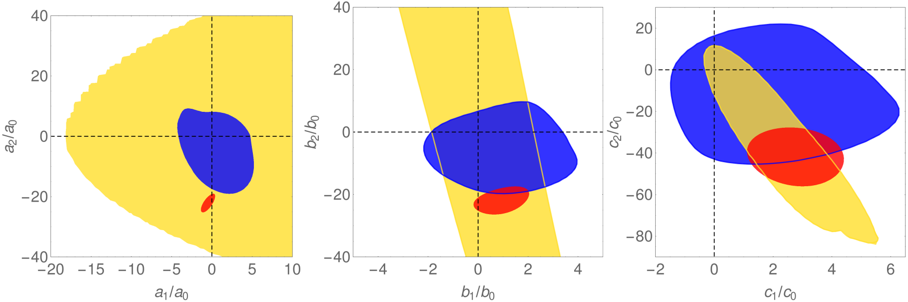



- $B \to D^*$ BGL coefficient ratios from:
  1. Data (Belle'17+'18) + weak unitarity (yellow)
  2. HQE theory fit 2/1/0 (red)
  3. HQE theory fit 3/2/1 (blue)

➥ 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:

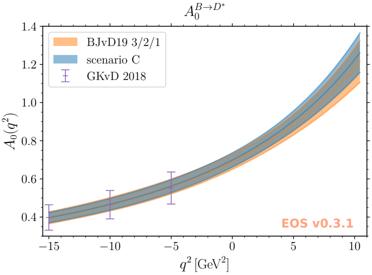
- Available lattice data:
  (2 $\bar{B}_s \to D_s$ FFs ($q^2$ dependent), 1 $\bar{B}_s \to D^*$ FF (only $q^2_{\rm max}$))
- Adaptation of existing QCDSR results [Ligeti/Neubert/Nir'93'94] , including SU(3) breaking
- New LCSR results extending [Gubernari+'18] to $B_s$, including SU(3) breaking

- 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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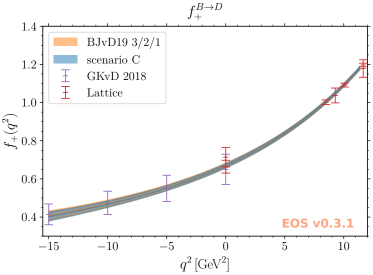


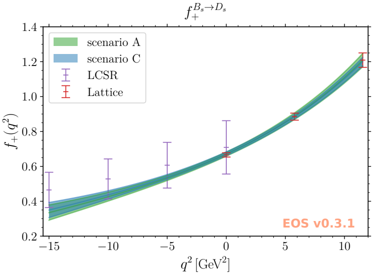

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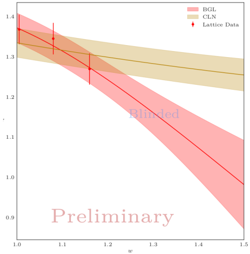
Theory-only predictions:

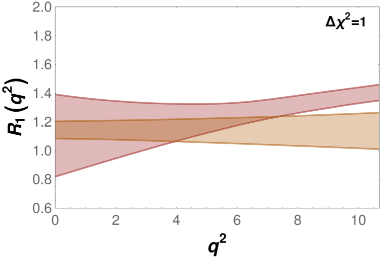
$$R(D) = 0.299(3) \qquad R(D^*) = 0.247(5)$$
$$R(D_s) = 0.297(3) \qquad R(D_s^*) = 0.245(8)$$

Theory+Experiment (Belle'17) predictions:

$$R(D) = 0.298(3) \qquad R(D^*) = 0.250(3)$$
$$R(D_s) = 0.297(3) \qquad R(D_s^*) = 0.247(8)$$

# Comparison with preliminary lattice calculations




$R_1(w)$: FNAL slope surprising, compatible at 1-2$\sigma$

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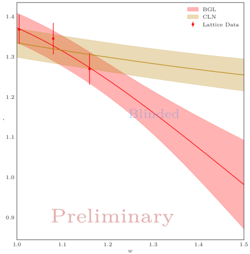


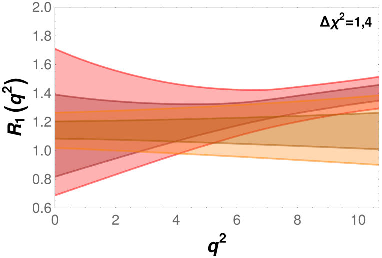


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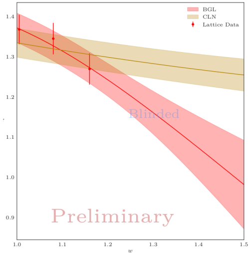


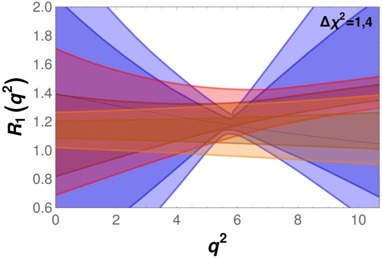


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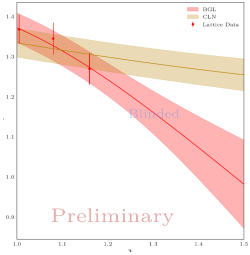


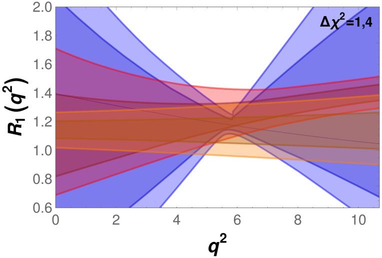


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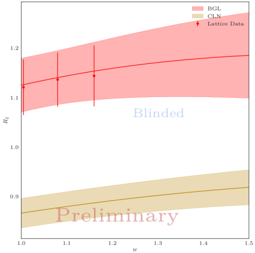


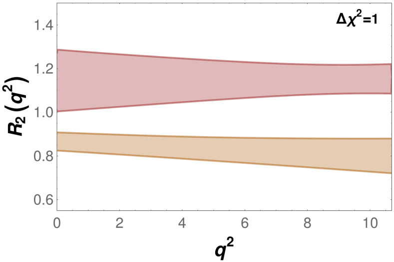


$R_2(w=1)$: Discrepancy FNAL $(1.12 \pm 0.06)$ vs. (HQE fit, experiment)!
HQE@$1/m_c^2$: $0.78^{+0.10}_{-0.06}$, BGL: $0.81 \pm 0.11$, HFLAV: $0.852 \pm 0.018$

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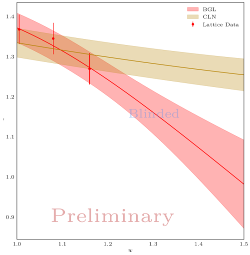


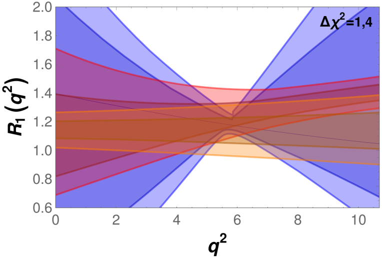


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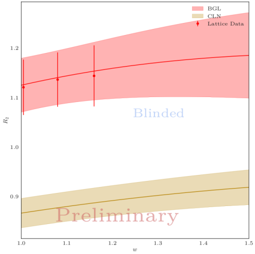


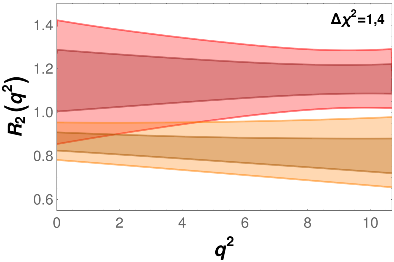


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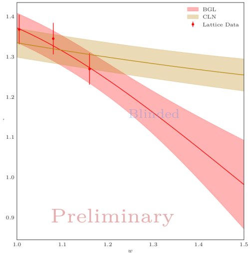


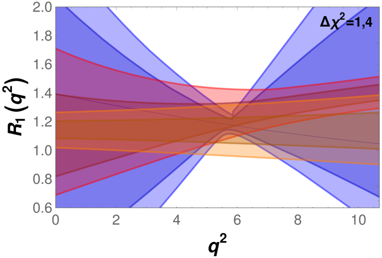


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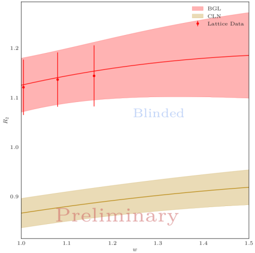
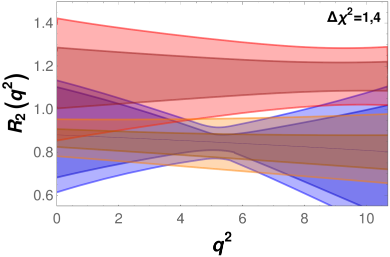



$R_2(w=1)$: Discrepancy FNAL $(1.12 \pm 0.06)$ vs. (HQE fit, experiment)!

HQE@$1/m_c^2$: $0.78^{+0.10}_{-0.06}$, BGL: $0.81 \pm 0.11$, HFLAV: $0.852 \pm 0.018$

# Flavour universality in $B \to D^*(e, \mu)\nu$

[Bobeth/Bordone/Gubernari/MJ/vDyk'21]

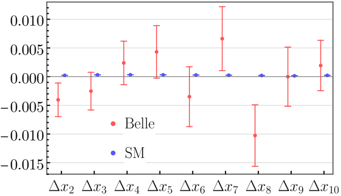
So far: Belle'18 data used in SM fits, flavour-averaged

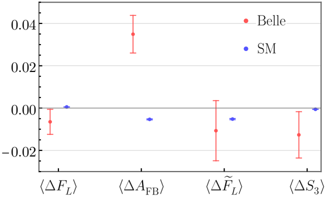
However: Bins $40 \times 40$ covariances given separately for $\ell = e, \mu$

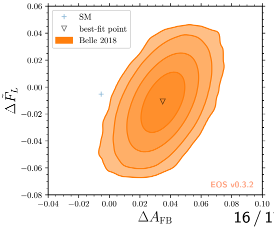
- Belle'18: $R_{e/\mu}(D^*) = 1.01 \pm 0.01 \pm 0.03$
- What can we learn about flavour-non-universality? $\to$ 2 issues:
  1. $e - \mu$ correlations not given $\to$ constructable from Belle'18
  2. 3 bins linearly dependent, but covariances not singular

Two-step analysis:

1. Extract $2 \times 4$ angular observables for $2 \times 30$ angular bins
   - Model-independent description including NP!
2. Compare with SM predictions, using FFs@$1/m_c^2$ [Bordone+'19]
   - $\sim 4\sigma$ discrepancy in $\Delta A_{\rm FB} = A_{\rm FB}^{\mu} - A_{\rm FB}^{e}$



# Conclusions

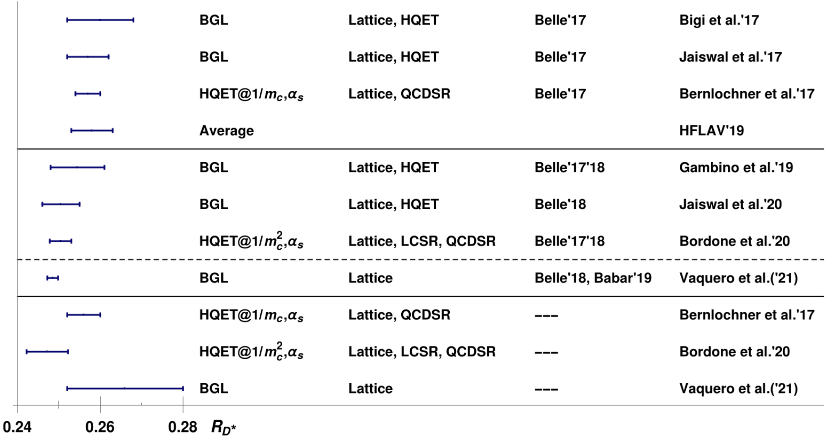
Form factors essential ingredients in precision-flavour physics!

- $q^2$ dependence critical $\rightarrow$ need FF-independent data
- ➥ Inclusion of higher-order (theory) uncertainties important
- BGL: model-independent, truncation uncertainty limited
- ➥ $B \rightarrow D^*$: Reduced $V_{cb}$ puzzle, somewhat lower $R(D^*)$ prediction
- Theory determinations for NP required $\rightarrow$ HQE to relate FFs
- $\mathcal{O}(1/m_c)$ not good enough for precision analyses
- ➥ First analysis at $1/m_c^2$ provides all $B \rightarrow D^{(*)}$ FFs
- ➥ $V_{cb}$ consistent w/ BGL
- First LQCD analyses in $B \rightarrow D^*$ and $B_s \rightarrow D_s^*$ @ finite $q^2$
- ➥ Tension with experiment as well as other theory inputs
- LFU-violation in $b \rightarrow c\ell\nu$@$\sim 4\sigma$!
- ➥ Experimental issues? NP?

Central lesson: experiment and theory need to work closely together!

Thank you & Happy birthday Alex!

# Overview over predictions for $R(D^*)$




Lattice $B \to D^*$: $h_{A_1}(w=1)$ [FNAL/MILC'14,HPQCD'17]
Other lattice: $f_{+,0}^{B\to D}(q^2)$ [MILC,HPQCD'15]
QCDSR: [Ligeti/Neubert/Nir'93,'94] , LCSR: [Gubernari/Kokulu/vDyk'18]

Consistent SM predictions! Improvement expected from lattice FNAL/MILC('21) discussed in the following.

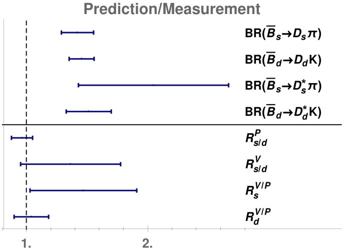
# A puzzle in non-leptonic $b \to c$ transitions

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

FFs also of central importance in non-leptonic decays:

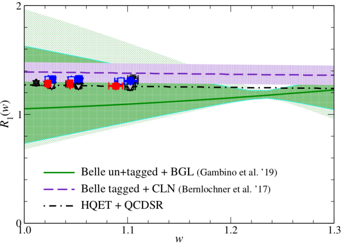
- Complicated in general, $B \to M_1 M_2$ dynamics
- Simplest cases: $\bar{B}_d \to D_d^{(*)} \bar{K}$ and $\bar{B}_s \to D_s^{(*)} \pi$ (5 diff. quarks)
  - Colour-allowed tree, $1/m_b^0 @ \mathcal{O}(\alpha_s^2)$ [Huber+'16] , factorizes at $1/m_b$
  - Amplitudes dominantly $\sim \bar{B}_q \to D_q^{(*)}$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

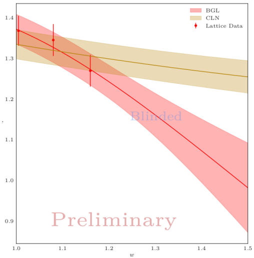
Updated and extended calculation: tension of $4.4\sigma$ w.r.t. exp.!

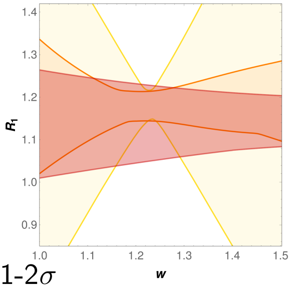



- Large effect, $\sim -30\%$ for BRs
- Ratios of BRs ok
- QCDf uncertainty $\mathcal{O}(1/m_b^2, \alpha_s^3)$
- Data consistent (too few abs. BRs)
- NP? $\Delta_P \sim \Delta_V \sim -20\%$ possible
- We will learn something important!

# Preliminary lattice calculations

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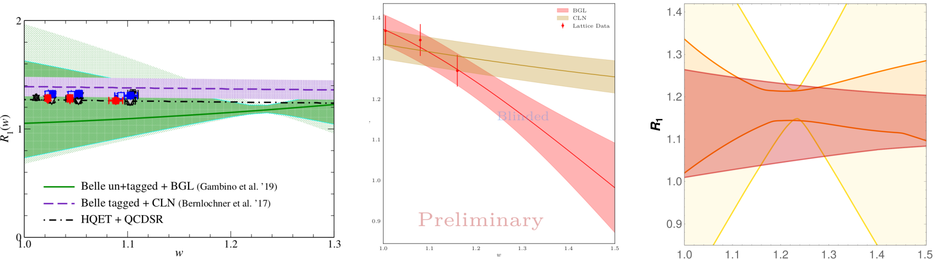


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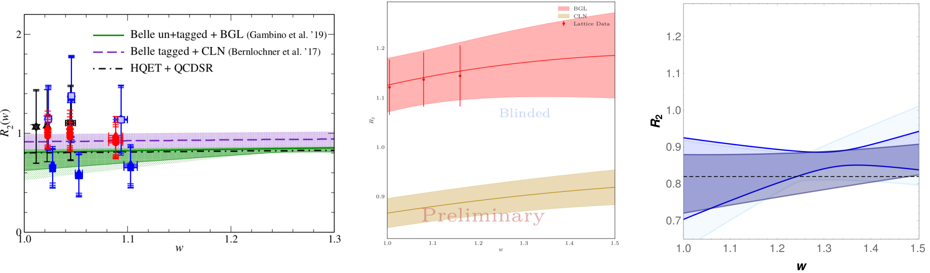


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# Comments regarding systematics and fitting [MJ/Straub'18]

Present (and future!) precision renders small effects important:

- Form factor parametrization
- d'Agostini effect:
  assuming systematic uncertainties $\sim$ (exp. cv) introduces bias
  ➥ e.g. 1-2$\sigma$ shift in $|V_{cb}|$ in Belle 2010 binned data
- Rounding in a fit with strong correlations and many bins:
  ➥ 1$\sigma$ between fit to Belle 2017 data from paper vs. HEPdata
- BR measurements and isospin violation [MJ 1510.03423] :
  Normalization depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
  Taken into account, but simple HFLAV average problematic:
  - Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
  - Measurements in $r_{+0}^{\mathrm{HFAG}}$ assume isospin in exclusive decays
    ➥ This is one thing we want to test!

  ➥ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
  (potentially subject to change, in contact with Belle members)

  ➥ Relevant for **all** BR measurements at the %-level

# BR measurements and isospin violation [MJ 1510.03423]

Detail due to high precision and small NP

➥ Relevant for $\sigma_{\mathrm{BR}}/\mathrm{BR} \sim \mathcal{O}(\%)$

Branching ratio measurements require normalization...

- $B$ factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from $B$ factories

Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: assumes $f_u \equiv f_d$, uses $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$

Both approaches problematic:

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in $r_{+0}^{\mathrm{HFAG}}$ assume isospin in exclusive decays
  ➥ This is one thing we want to test!

➥ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
(potentially subject to change, in contact with Belle members)

# Generalities regarding this anomaly

$\sim 15\%$ of a SM tree decay $\sim V_{cb}$: This is a huge effect!
➥ Need contribution of $\sim 5-10\%$ (w/ interference) or $\gtrsim 40\%$ (w/o interference) of SM

What do we do about this?

- Check the SM prediction!
  [→ Bigi+,Bordone+,Gambino+,Grinstein+,Bernlochner+]
  ➥ $\delta R(D^*)$ larger, anomaly remains
- Combined analysis of all $b \to c\tau\nu$ observables [100+ papers]
  ➥ First model discrimination
- Related indirect bounds (partly model-dependent)
  ➥ High $p_T$ searches, lepton decays, LFV, EDMs, ...
- Analyze flavour structure of potential NP contributions
  ➥ quark flavour structure, e.g. $b \to u$
  ➥ lepton flavour structure, e.g. $b \to c\ell(=e,\mu)\nu$