Key open questions for the current measurements and predictions of $R(D^{(*)})$

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MARIE CURIE ACTIONS

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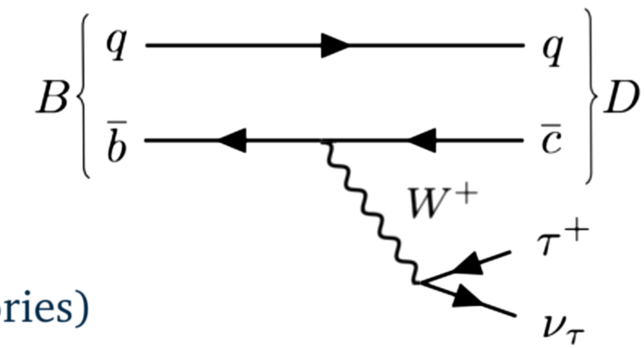
Beyond the flavour anomalies
Durham, 27th of April 2022

Lepton Flavour Universality tests with semi-tauonic decays

$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$



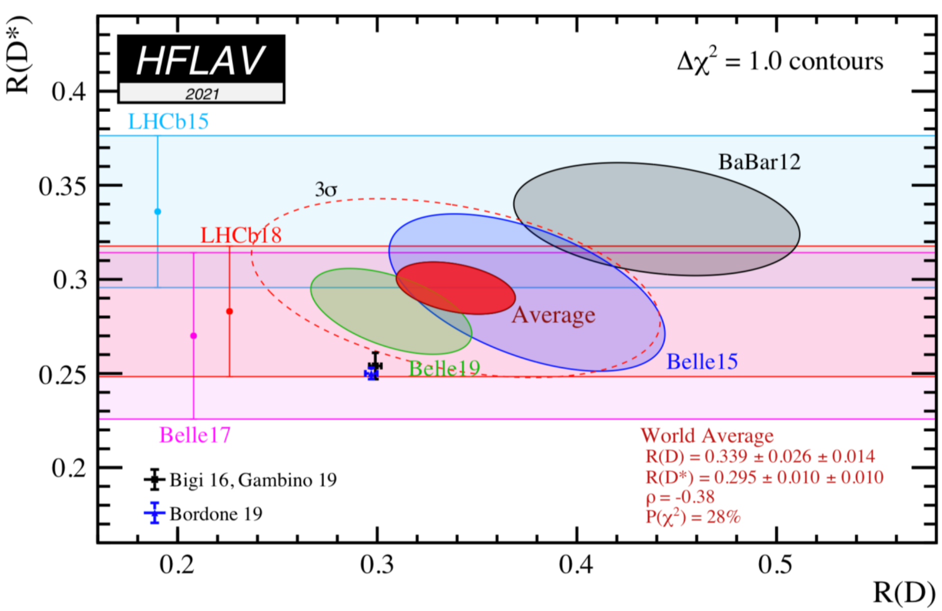
$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s ...$

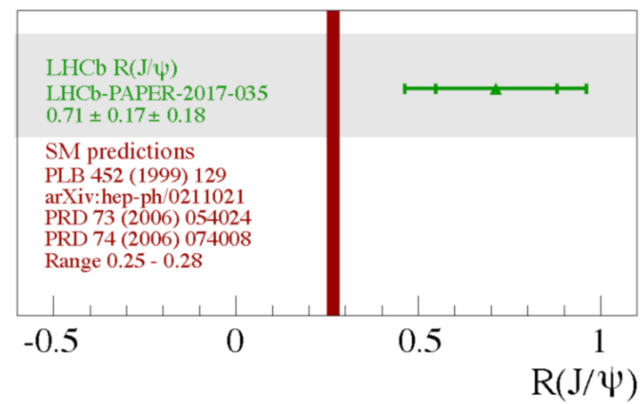
$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda^{(*)}_c, J/\psi ...$

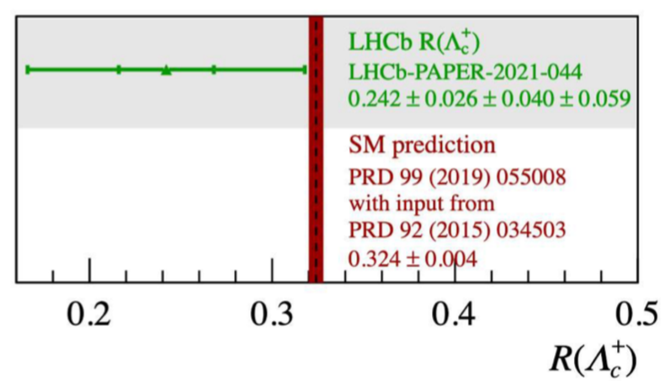
ℓ' = μ (LHCb)

ℓ' = e/μ (B-factories)

Measurements from the B factories and LHCb.
Tension in $R(D^{(*)})$ at the level of **> 3σ**.



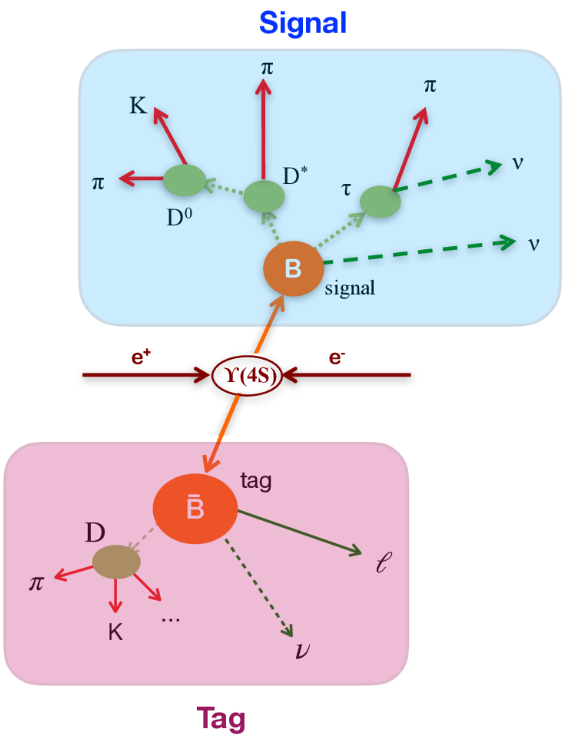




Experimental methods

B-factories

- e^+/e^- collision produces $\Upsilon(4S) \rightarrow B\overline{B}$
- Fully reconstruct one of the two B-mesons ('tag') ➝ **possible** to **assign all particles** to either signal or tag B
- **B rest frame** can be reconstructed with high precision



LHCb

No constraint from beam energy.

Rest-frame approximation:

$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

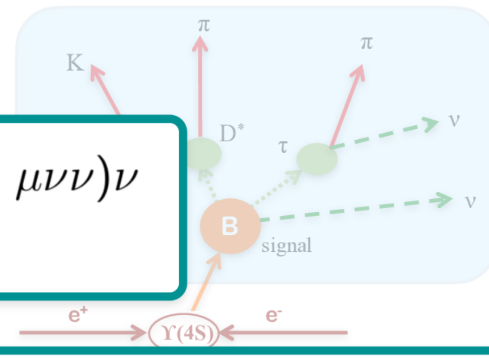
combined with known B flight direction (from vertex reconstruction).

Isolation tools to reduce backgrounds with extra charged tracks or neutrals.

Experimental methods

B-factories

- e^+/e^- collision produces $Y(4S) \rightarrow B\overline{B}$



- Difficulty: neutrinos - 2 for $(\tau \to \pi\pi\pi\nu)\nu$, 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)

- Missing four omentum (neu
can be recons ucted with high

- Main backgrounds: partially reconstructed B decays
  - $B \to D^*\mu\nu, B \to D^{**}\mu\nu$, $B \to D^* D(\to \mu X)X$ ...
  - $B \to D^*\pi\pi\pi X$, $B \to D^* D(\to \pi\pi\pi X)X$ ...
- Also combinatorial, misidentified background

LHCb

No constraint from beam energy.

Tag

Rest-frame approximation:

$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

combined with known B flight direction (from vertex reconstruction).

Isolation tools to reduce **backgrounds** with extra charged tracks or neutrals.

Observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

[arXiv:2201.03497]

Newest result, from the LHCb collaboration.

$$\mathcal{R}(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c \mu \nu_\mu)}$$

Decay	$\mathcal{B}$ (%)
$\tau^- \to \pi^-\pi^+\pi^- \nu_\tau$	9.02 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\pi^0 \nu_\tau$	4.49 ± 0.05

Similar strategy to hadronic R(D*) measurement.

signal

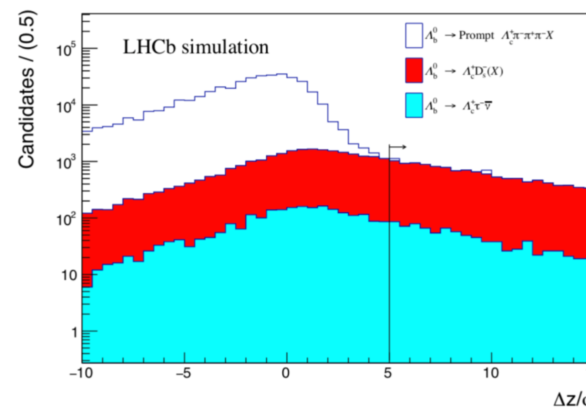
$$\mathcal{R}(\Lambda_c) = \left(\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}\right)_{\text{measured}} \times \left(\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}\right)_{\text{external}}$$

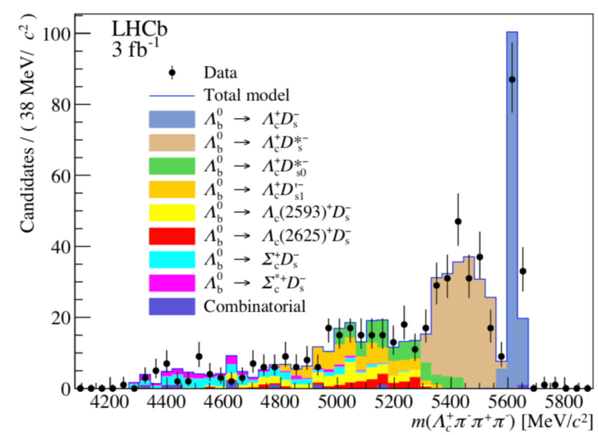
normalisation

➔ Suppress prompt background with cut on distance between vertices.

➔ Remaining main background from $\Lambda_b \to X_c X_c$ decays, controlled by selecting events around a fully reconstructed D_s^+ peak.

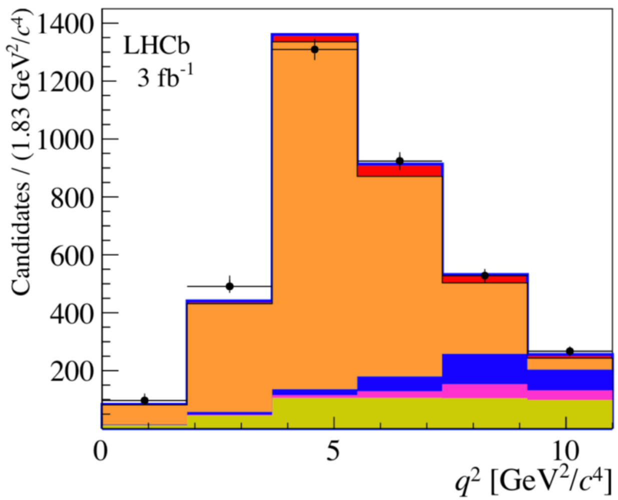
➔ 3D fit to q^2, tau decay time and output of a BDT against D_s backgrounds.



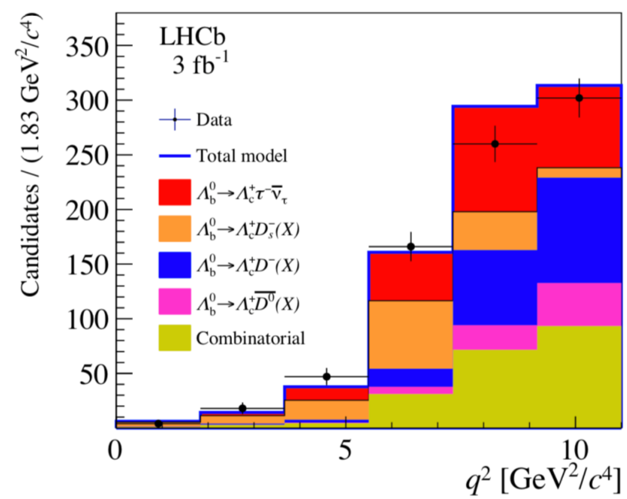


Observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ [arXiv:2201.03497]

Low BDT region



High BDT region



$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c \tau^- \bar{\nu}_\tau) = (1.50 \pm 0.16(\text{stat}) \pm 0.25(\text{syst}) \pm 0.23(\text{ext}))\ \%$$

$$\mathscr{R}(\Lambda_c) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$$

➔ **First observation of this mode.**

➔ **Compatible with the SM expectation within 1σ.**

Note: Run 1 only analysis, plenty of room for more precision with Run 2 data and with the complementary $\tau \to \mu\nu\nu$ mode.

Upcoming analyses

➔ **LHCb:**

- ➥ Combined R(D^0) vs R(D^{*+}), muonic tau, $D^{*+} \to D^0 \pi^+$ (update of previous analysis).
- ➥ Combined R(D^+) vs R(D^{*+}), muonic tau, $D^{*+} \to D^+ \pi^0$ / $D^+ \gamma$.

Two elipses in the R(D) vs R(D*) plain with **different correlation**.

- ➥ Update of hadronic-tau R(D^{*+}).
- ➥ Measurement of the D^{*+} polarisation with hadronic-tau decays (previously measured by Belle [arXiv:1903.03102]).
- ➥ Others: $B \to D^{**}\tau\nu$ (narrow states), $B_s \to D_s^{(*)}\tau\nu$, $\Lambda_b \to \Lambda_c^{(**)}\tau\nu$, update of R($J/\psi$), …

➔ **BaBar** to deliver another precise, more data-driven, measurement of R($D^{(*)}$) (see talk from Yunxuan Li at Moriond EW 2022).

➔ Work on R(D*) and R(J/ψ) at **CMS** (see Yuta's talk tomorrow).

➔ **Belle II** has already accumulated $\mathscr{L}_{int}$ ~1/4 of Belle full dataset, many future plans (see Florian's talk tomorrow).

How can the measurements of $R(D^{(*)})$ be improved?

Shape of the $B \to D$ and $B \to D^*$ signal and normalisation components.

Composition and shape of the $B \to D^{**}$ backgrounds (muonic and tauonic).

Composition of the double-charm backgrounds.

How can the measurements of $R(D^{(*)})$ be improved?

Shape of the B→D and B→D* signal and normalisation components.

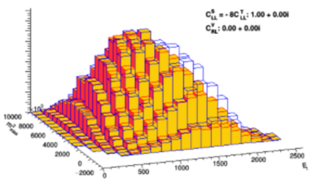
Form factor (FF) parameters (I)

Template shapes in experimental fits **dependent on FF parameters** (and Wilson coefficients in the case of NP fits).

Huge background and resolution effects on semitauonic decays. → Instead of unfold, **forward fold** your preferred model.

➥ **HAMMER tool** [Eur.Phys.J.C 80 (2020) 9].
➥ **RooHammerModel** (interface betweenHAMMER and HistFactory/RooFit) [2022 JINST 17 T04006].

Helicity Amplitude Module for Matrix Element Reweighting



Q1: how to minimize the impact from the choice of a form-factor parameterisation?
At present, BGL/BCL models are used, typically with a quadratic expansion.
➥ As the precision increases with more data, this may not be enough anymore.

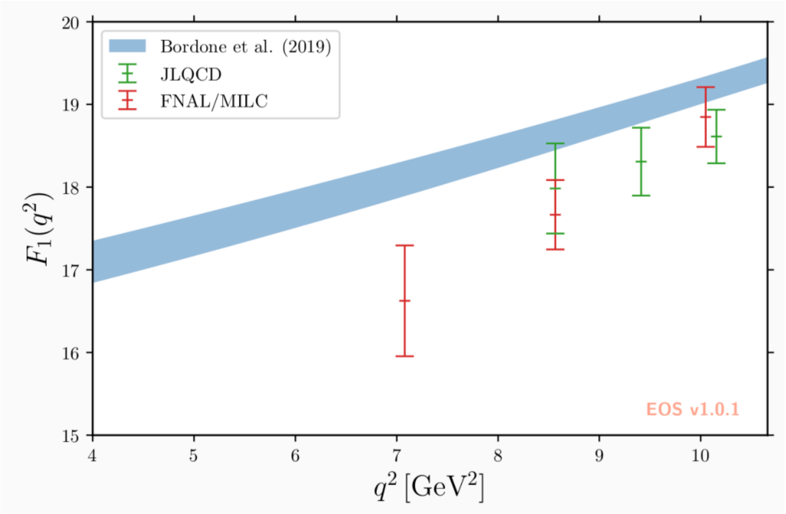
How can the measurements of $R(D^{(*)})$ be improved?

Shape of the B→D and B→D* signal and normalisation components.

Form factor parameters (II)

External constraints help to reduce the uncertainties, **specifically those associated to the scalar FF** (only tauonic modes), for which there is almost no experimental sensitivity.

Recently, first LQCD results for B→D* at non-zero recoil were made available by **FNAL/MILC** [arXiv:2105.14019], later followed by **JLQCD** [still to appear] and **HPQCD** [still to appear] (see last week's talk from Judd Harrison).



Problem: tensions across computations and previous measurements.

Q2: how to best use the information from B→D* LQCD computations in current experimental measurements?

How can the measurements of R(D$^{(*)}$) be improved?

Shape of the B→D and B→D* signal and normalisation components.

Form factor parameters (III)

The past measurements have assumed SM distributions.
There are several ongoing measurements in LHCb that aim at also fitting for **Wilson coefficients**. → Need for predictions of the **FF for the NP terms**.

Currently, only **BLPR** [Phys. Rev. D 95, 115008 (2017)] parameterisation available in HAMMER.

New HQE-based parameterisations including systematically **1/m_c^2 corrections** [arXiv:1908.09398] [arXiv:1912.09335] can help reducing the uncertainties.

Q3: can NP FF parameterisations with 1/m_c^2 corrections be implemented in HAMMER?

How can the measurements of $R(D^{(*)})$ be improved?

Shape of the $B \to D$ and $B \to D^*$ signal and normalisation components.

QED corrections

As measurements become more precise, QED corrections to the decay distributions become more relevant.

1. **Coulomb correction**: can be computed analytically. Correction functions for $B \to D$ have been obtained in [Eur.Phys.J.C 79 (2019) 9, 744].

2. **Other effects (soft photon emission …)**: partly included in PHOTOS (and taken into account in HAMMER).

Q4: are there any plans regarding the study of QED effects beyond the Coulomb interaction which are not included in PHOTOS?

How can the measurements of R(D$^{(*)}$) be improved?

Common aspects to B → D$\mu\nu$ and B → D**$\tau\nu$, with D** $\in$ {D_0^*, D_1, D_1', D_2^*}**

The decay structure of the D** modes is **poorly known**. → Studied in dedicated control samples in each analysis, using some assumptions in the modeling.

Future experimental measurements and LQCD computations of these modes can significantly help reducing the associated systematic uncertainties.

Composition and shape of the B→D** backgrounds (muonic and tauonic).

B → D$\tau\nu$ modes**

The R(D**) ratio has never been measured. In R(D(*)) analyses, the yield of the tauonic feed down is typically **constrained to the SM expectation with a large uncertainty**.

Ongoing LHCb measurement of **B → D**$\tau\nu$ with the narrow D** states**, D_1 and D_2^*.
Q5: can the R(D(*)) uncertainty from B → D$\tau\nu$ feed down be (safely) reduced with certain experimental measurements?** (See discussion in [arXiv:2101.08326]).

How can the measurements of $R(D^{(*)})$ be improved?

Possibility of analysis combinations (I)

The structure of $X_b \to X_c X_c$ decays is in general **poorly known**, and is controlled in each analysis through the study of devoted data regions.

Significant systematic uncertainties can arise due to the **limited sample size**, and/or due to the **assumptions needed for extrapolations** to the signal regions.

Possibility to reduce the uncertainties by doing simultaneous analyses of channels with partially different $X_b \to X_c X_c$ feed down contributions: combination of different isospin-related modes (e.g. D^0 and D^+), different tauonic-decay modes, different experimental conditions (e.g. LHCb and Belle II, see last week's talk by Florian), …

➥ The modeling of other components, such as the D^{**} modes, could also be shared across channels, further reducing the associated uncertainties.

Q6: which type of analysis combinations would be more convenient?

Composition of the double-charm backgrounds.

How can the measurements of R(D$^{(*)}$) be improved?

Possibility of analysis combinations (II)

Following such a challenging future road would require the **development of future common tools**.

Possible example: the **Deep-learning based Full Event Interpretation (DFEI)** project (see this presentation), that aims at doing a hierarchical reconstruction of the heavy-hadron decay chains in **LHCb** events (similar to Belle II, but much more challenging).

LHCbDFEI goals:

- **Combined charged-neutral isolation** capabilities, through a global event interpretation.
- **“Automatic” selection/separation of different channels**, based on topology matching.

Composition of the double-charm backgrounds.

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?

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

$B \to D\ell\nu$ and $R(D)$ prediction

$B \to D\ell\nu$, aka "What it should look like":

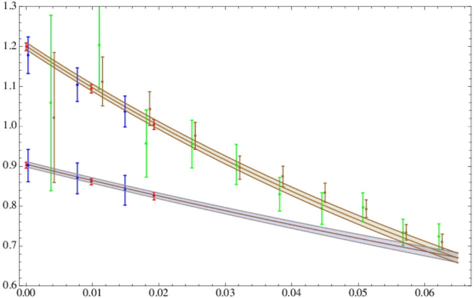
- Excellent agreement between experiments [BaBar'09,Belle'16]
- Excellent agreement between two lattice determinations [FNAL/MILC'15,HPQCD'16]

➥ Lattice data contradict CLN parametrization! (Not HQE@1/m, discussed later)

- BGL fit [Bigi/Gambino'16] :

$$R(D) = 0.299(3)\,. \quad (\text{Exp.: } 0.339(26)(14))$$

See also [Jaiswal+,Berlochner+'17,MJ/Straub'18,Bordone/MJ/vanDyk'19]



$f_{+,0}(z)$, inputs:

- FNAL/MILC'15
- HPQCD'16
- BaBar'09
- Belle'16

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

[Bordone/MJ/vanDyk'19,Bordone/Gubernari/MJ/vanDyk'20]

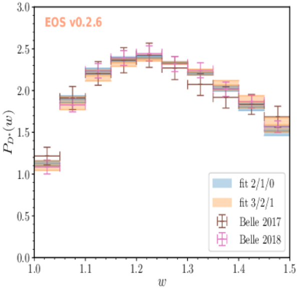
To determine general NP, FF shapes needed from theory!

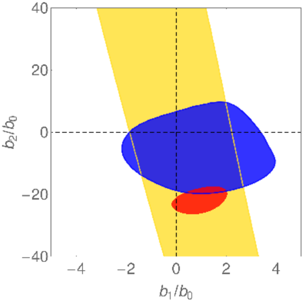
Fit to all $B \to D^{(*)}$ FFs, using lattice, LCSR, QCDSR and unitarity

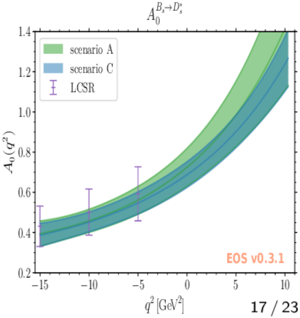
[CLN,BGL,HPQCD'15'17,FNAL/MILC'14'15,Gubernari+'18,Ligeti+'92'93]

k/l/m order in z for leading/subleading/subsubleading IW functions

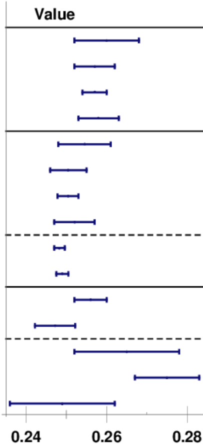
- 2/1/0 works, but only 3/2/1 captures uncertainties
- Consistent V_{cb} value from Belle'17+'18
- Predictions for diff. rates, perfectly confirmed by data
- Explicit inclusion of $B_s \to D_s^{(*)}$: improvement for all FFs







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



Method	Input Theo	Input Exp	Reference
BGL	Lattice, HQET	Belle'17	Bigi et al.'17
BGL	Lattice, HQET	Belle'17	Jaiswal et al.'17
HQET@$1/m_c,\alpha_s$	Lattice, QCDSR	Belle'17	Bernlochner et al.'17
Average			HFLAV'19
BGL	Lattice, HQET	Belle'17'18	Gambino et al.'19
BGL	Lattice, HQET	Belle'18	Jaiswal et al.'20
HQET@$1/m_c^2,\alpha_s$	Lattice, LCSR, QCDSR	Belle'17'18	Bordone et al.'20
Average			HFLAV'21
BGL	Lattice	Belle'18, Babar'19	Vaquero et al.'21v2
BGL	Lattice	Belle'18	MJ (JLQCD prel.)
HQET@$1/m_c,\alpha_s$	Lattice, QCDSR	---	Bernlochner et al.'17
HQET@$1/m_c^2,\alpha_s$	Lattice, LCSR, QCDSR	---	Bordone et al.'20
BGL	Lattice	---	Vaquero et al.'21v2
DM	Lattice	---	Martinelli et al.
BGL	Lattice	---	MJ (JLQCD prel.)

Lattice $B \to D^*$: $h_{A_1}(w=1)$ [FNAL/MILC'14,HPQCD'17] , [FNAL/MILC'21]

Other lattice: $f_{+,0}^{B\to D}(q^2)$ [FNAL/MILC,HPQCD'15]

QCDSR: [Ligeti/Neubert/Nir'93,'94] , LCSR: [Gubernari/Kokulu/vDyk'18]

Overall consistent SM predictions!
Even further improvement expected from lattice

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

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	BGL	Lattice	---	Vaquero et al.'21v2
	DM	Lattice	---	Martinelli et al.
	BGL	Lattice	---	MJ (JLQCD prel.)

Lattice $B \to D^*$: $h_{A_1}(w=1)$ [FNAL/MILC'14,HPQCD'17] , [FNAL/MILC'21]

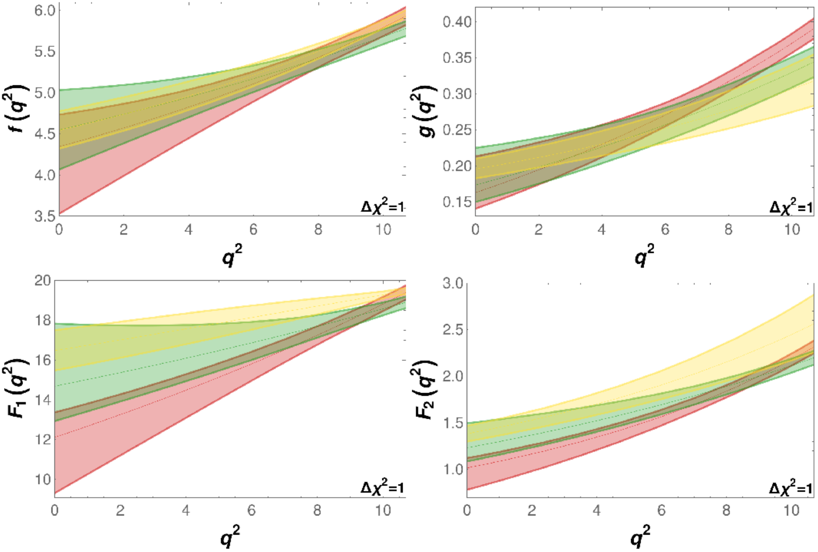
Other lattice: $f_{+,0}^{B\to D}(q^2)$ [FNAL/MILC,HPQCD'15]

QCDSR: [Ligeti/Neubert/Nir'93,'94] , LCSR: [Gubernari/Kokulu/vDyk'18]

Overall consistent SM predictions!
Even further improvement expected from lattice

Comparison form factor fits

Major recent progress: 3 lattice calculations at finite recoil!

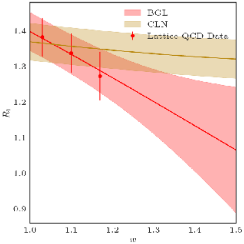


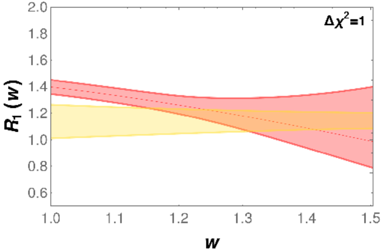
FNAL/MILC'21, HQE@$1/m_c^2$, JLQCD prel

Comparison with new lattice calculations

Major improvement: $B \to D^*_{(s)}$ FFs@$w > 1$!

[HPQCD'21,FNAL/MILC'21,JLQCD prel.]



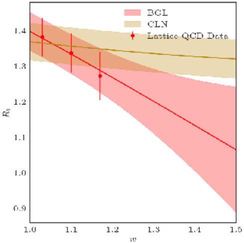


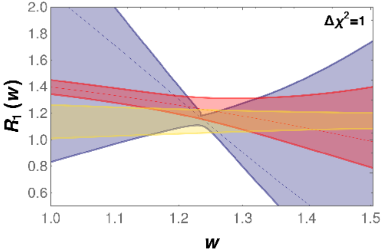
- FNAL/MILC'21
- HQE@$1/m_c^2$
- Exp (BGL)
- JLQCD prel

Comparison with new lattice calculations

Major improvement: $B \to D^*_{(s)}$ FFs@$w > 1$!

[HPQCD'21,FNAL/MILC'21,JLQCD prel.]





- FNAL/MILC'21
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- Exp (BGL)
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Comparison with new lattice calculations

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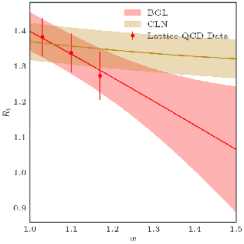

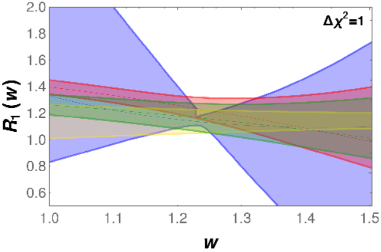

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- ➥ Compatible. Slope?

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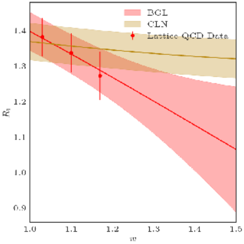

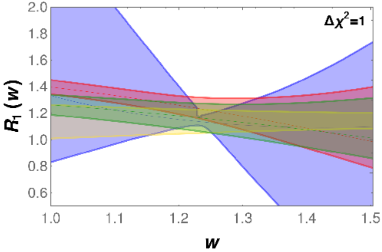

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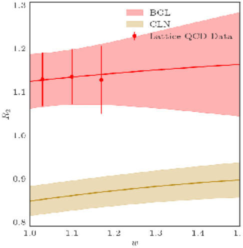

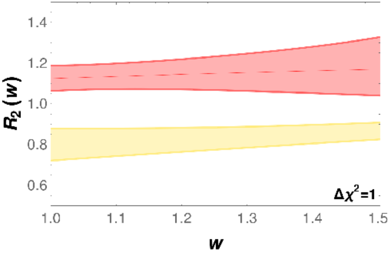

- Deviation wrt previous FFs

Comparison with new lattice calculations

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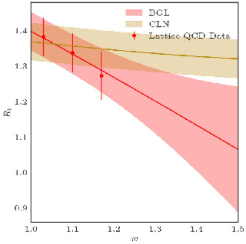

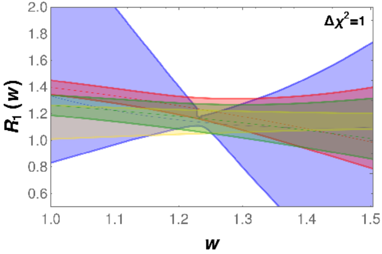

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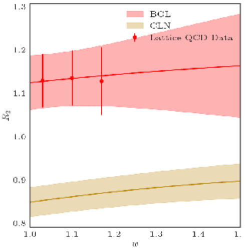
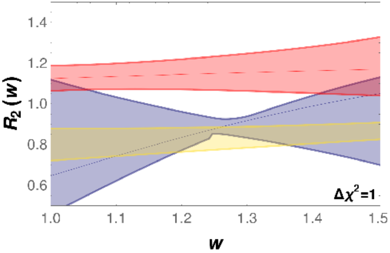


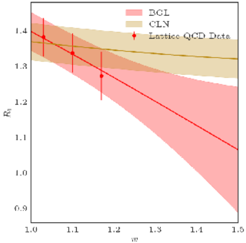


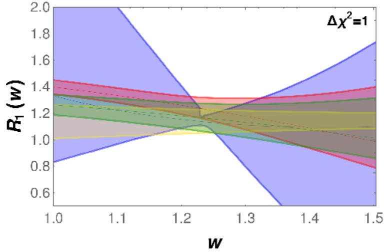
- Deviation wrt previous FFs
- Deviation wrt experiment

Comparison with new lattice calculations

Major improvement: $B \to D^*_{(s)}$ FFs@$w > 1$!

[HPQCD'21,FNAL/MILC'21,JLQCD prel.]





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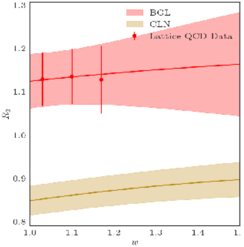
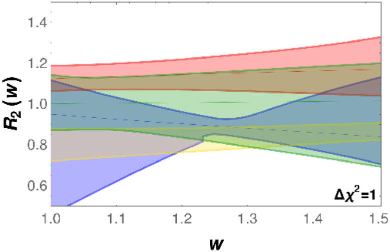




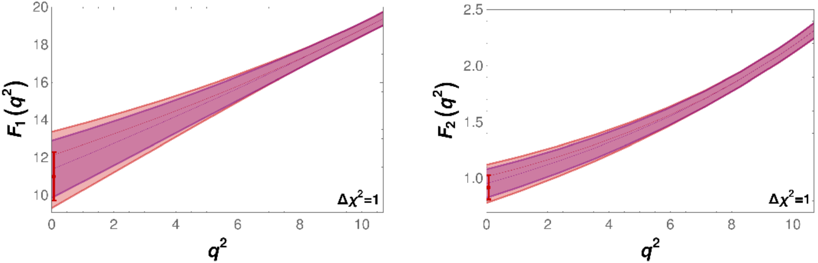
- Deviation wrt previous FFs
- Deviation wrt experiment
- JLQCD "diplomatic"

➥ Requires further investigation! Combination difficult.

Priors and potential biases

Different conclusions starting from identical information

Example: $R(D^*)$ extraction from FNAL/MILC data



$R(D^*)$ including kinematical identities and weak unitarity

$$R(D^*) \stackrel{\text{WU}}{=} 0.269^{+\mathbf{0.020}}_{-0.008} \quad \stackrel{\text{FM}}{=} 0.274 \pm 0.010 \quad \stackrel{\text{Rome}}{=} 0.275 \pm 0.008\,.$$

Difference WU-FM: FM apply prior on BGL coefficients

Difference WU-Rome (educated guess): iterated “unitarity filter”

Applying data: $R(D^*) = 0.249 \pm 0.001(!)$ universally.

D’Agostini bias: needs to be treated!

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

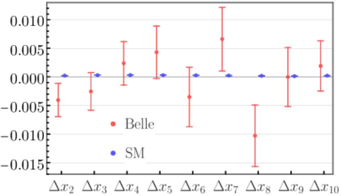
However: Bins 40×40 covariances given separately for $\ell = e, \mu$

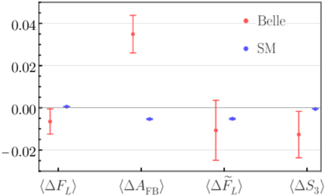
- Belle'18: $R_{e/\mu}(D^*) = 1.01 \pm 0.01 \pm 0.03$
- What can we learn about flavour-non-universality? $\to$ 2 issues:

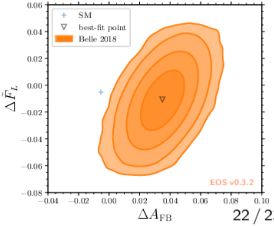
1. $e - \mu$ correlations not given $\to$ constructable from Belle'18
2. 3 bins linearly dependent, but covariances not singular

Two-step analysis:

1. Extract 2×4 angular observables for 2×30 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
- 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
- $R(D)$ prediction: full agreement, small uncertainty
- First LQCD analyses in $B \rightarrow D^*$ (and $B_s \rightarrow D_s^*$) @ finite recoil
- ➥ FNAL/MILC: Tension with experiment and HQE
- ➥ JLQCD prel.: Agreement

$R(D^*)$ cannot be SM unless $B \rightarrow D^* \ell\nu$ are NP or exp. wrong!

- LFU-violation in $b \rightarrow c\ell\nu$@$\sim 4\sigma$!
- ➥ Experimental issues? NP?

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

Backup slides

Tension between experiment and theory

From Judd Harrison's talk at the "Challenges in Semileptonic B decays 2022" Workshop:

	Lattice only	Lattice+Exp[5]	Experiment	Tension
$R(D)$	0.293(4)[6]	0.299(3)	0.340(30)	1.4σ
$R(D^*)$	0.265(13)	0.2483(13)	0.295(14)	3.3σ
$R(D_s)$	0.299(5)	–	–	–
$R(D_s^*)$	0.249(7)	–	–	–
$R(J/\psi)$	0.258(4)	–	0.71(25)[7]	1.8σ

HFLAV average, Fermilab-MILC, HPQCD.

[5] Assumes new physics only possible in semitauonic mode
[6] FLAG review
[7] LHCb-1711.05623

Systematics on the $\Lambda_b \to \Lambda_c \tau \nu$ analysis [arXiv:2201.03497]

- Largest systematics come from template shape:
  - sample size and shape

Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\overline{\nu}_\tau$ feeddown	2.5
$D_s^- \to 3\pi Y$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^- , D^- , $\overline{D}^0$ template shapes	13.0
Efficiency ratio	2.8
Normalisation channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

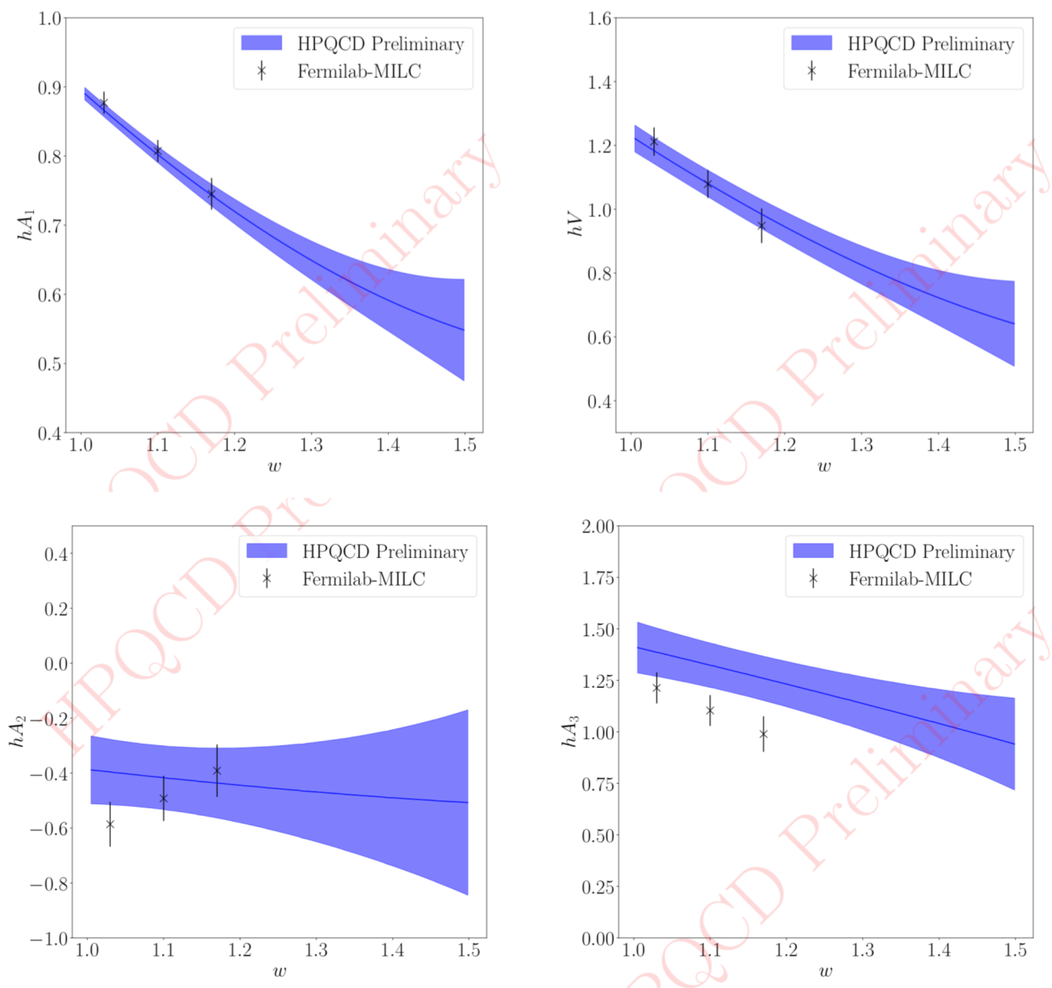
Systematics in R(D$^{(*)}$) across measurements

From Florian's talk at the "Challenges in Semileptonic B decays 2022" Workshop:

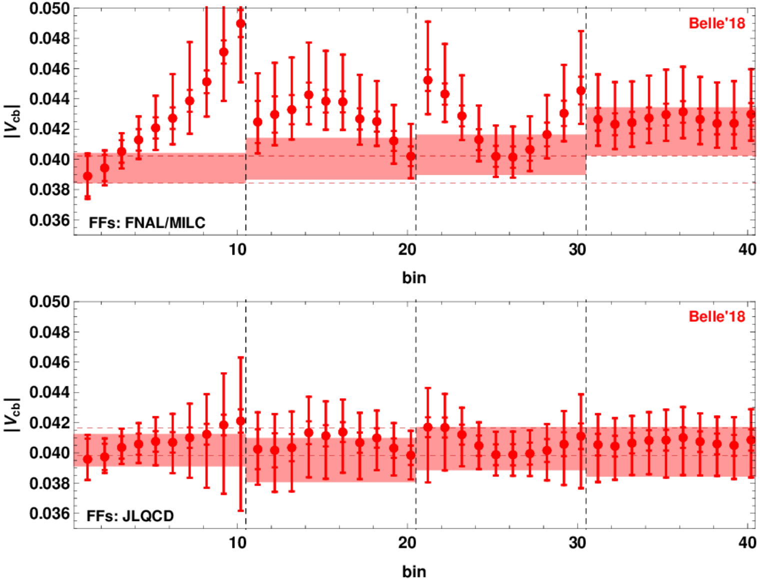
Result	Experiment	τ decay	Tag	Systematic uncertainty [%] MC stats	$D^{(*)}l\nu$	$D^{**}l\nu$	Other bkg.	Other sources	Total uncert. [%] Syst.	Stat.	Total
$\mathcal{R}(D)$	*BABAR* [a]	$\ell\nu\nu$	Had.	5.7	2.5	5.8	3.9	0.9	**9.6**	**13.1**	**16.2**
	Belle[b]	$\ell\nu\nu$	Semil.	4.4	0.7	0.8	1.7	3.4	**5.2**	**12.1**	**13.1**
	Belle[c]	$\ell\nu\nu$	Had.	4.4	3.3	4.4	0.7	0.5	**7.1**	**17.1**	**18.5**
$\mathcal{R}(D^*)$	*BABAR* [a]	$\ell\nu\nu$	Had.	2.8	1.0	3.7	2.3	0.9	**5.6**	**7.1**	**9.0**
	Belle[b]	$\ell\nu\nu$	Semil.	2.3	0.3	1.4	0.5	4.7	**4.9**	**6.4**	**8.1**
	Belle[c]	$\ell\nu\nu$	Had.	3.6	1.3	3.4	0.7	0.5	**5.2**	**13.0**	**14.0**
	Belle[d]	$\pi\nu$, $\rho\nu$	Had.	3.5	2.3	2.4	8.1	2.9	**9.9**	**13.0**	**16.3**
	LHCb[e]	$\pi\pi\pi(\pi^0)\nu$	—	4.9	4.0	2.7	5.4	4.8	**10.2**	**6.5**	**12.0**
	LHCb[f]	$\mu\nu\nu$	—	6.3	2.2	2.1	5.1	2.0	**8.9**	**8.0**	**12.0**

HPQCD vs FNAL/MILC for B→D* form factors

From Judd Harrison's talk at the "Challenges in Semileptonic B decays 2022" Workshop:



Binned V_{cb} from Belle'18 data



Graphs for illustration purposes, only.

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!