Technische Universität München

Recent Progess on Form Factor and Charm Loop Uncertainties

08.06.2020

Danny van Dyk

Technische Universität München

based on

`arXiv:1908.09398`	with M. Bordone, M. Jung
`arXiv:1912.09335`	with M. Bordone, N. Gubernari, M. Jung
`arXiv:20xy.abcde`	with N. Gubernari, J. Virto

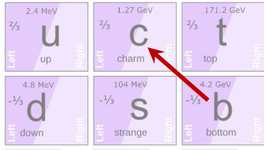
funded by

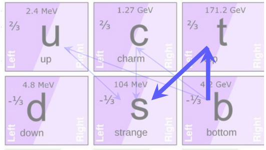
Deutsche Forschungsgemeinschaft

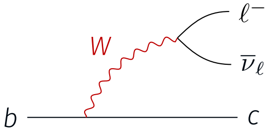
Emmy Noether-Programm

Introduction

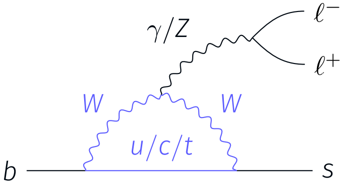
Semileptonic and radiative b decays (in theory)





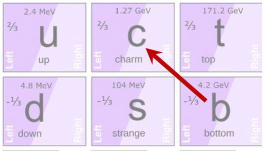


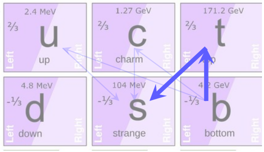
tree level

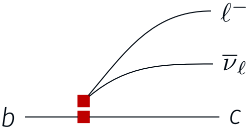


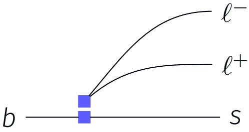
loop level

Semileptonic and radiative b decays (in theory)









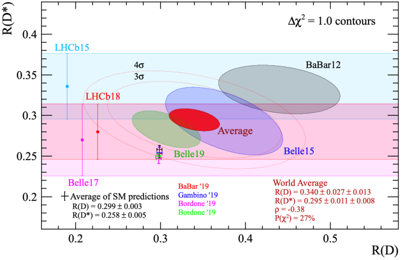
$$\sum_i \mathcal{C}_i \times [\bar{c}\, \Gamma_i\, b] \times \ldots$$

tree level

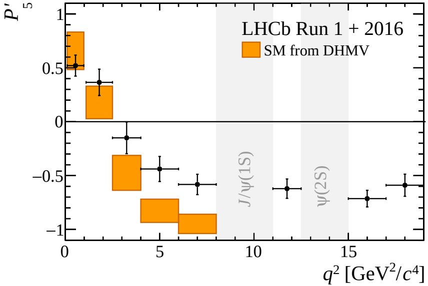
$$\sum_i \mathcal{C}_i \times [\bar{s}\, \Gamma_i\, b] \times \ldots$$

loop level

The anomalies in plots



[M. Rotondo for upcoming HFLAV update]



[E.A. Smith CERN Seminar '20; LHCb 2003.04831]

$$\sum_i \mathcal{C}_i \times [\bar{c}\,\Gamma_i\, b] \times \ldots \qquad \sum_i \mathcal{C}_i \times [\bar{s}\,\Gamma_i\, b] \times \ldots$$

Interpretation of the Wilson coefficients $\mathcal{C}_i$ requires knowledge of the hadronic matrix elements $\langle \ldots | \bar{c}\,\Gamma_i\, b\,| \ldots \rangle$ and $\langle \ldots | \bar{s}\,\Gamma_i\, b\,| \ldots \rangle$.

$\overline{B} \to D^{(*)}\ell^{-}\overline{\nu}$ Form Factors

Definitions

- SM requires 2 + 4 *form factors* for description of $D + D^*$ final states
  - form factors are functions dependent on q^2: the $\ell^-\overline{\nu}$ mass squared

$$\langle D(k)|\,\bar{c}\gamma^\mu b\,|B(p)\rangle = \left[(p+k)^\mu - \frac{M_B^2 - M_D^2}{q^2}q^\mu\right]\boxed{f_+(q^2)} + \frac{M_B^2 - M_D^2}{q^2}q^\mu \boxed{f_0(q^2)}$$

$$\langle D(k)|\,\bar{c}\sigma_{\mu\nu} b\,|B(p)\rangle = \frac{2i}{M_B + M_D}(k^\mu p^\nu - p^\mu k^\nu)\, f_T(q^2)$$

$$\langle D^*(k,\eta)|\,\bar{c}\gamma^\mu b\,|B(p)\rangle = -\epsilon^{\mu\nu\rho\sigma}\eta_{*\nu}(k)\,p_\rho\,k_\sigma \frac{2\boxed{V(q^2)}}{M_B + M_{D^*}}$$

$$\langle D^*(k,\eta)|\,\bar{c}\gamma^\mu\gamma_5 b\,|B(p)\rangle = i\eta^*_\nu\Big\{2M_{D^*}\boxed{A_0(q^2)}\frac{q^\mu q^\nu}{q^2} + 16\frac{M_B M_{D^*}^2}{\lambda}\boxed{A_{12}(q^2)}\left[2p^\mu q^\nu - \frac{M_B^2 - M_{D^*}^2 + q^2}{q^2}q^\mu q^\nu\right]$$
$$+ (M_B + M_{D^*})\boxed{A_1(q^2)}\left[g^{\mu\nu} + \frac{2(M_B^2 + M_{D^*}^2 - q^2)}{\lambda}q^\mu q^\nu - \frac{2(M_B^2 - M_{D^*}^2 - q^2)}{\lambda}p^\mu q^\nu\right]\Big\}$$

$$\langle D^*(k,\eta)|\,\bar{c}\sigma_{\mu\nu} b\,|B(p)\rangle = i\eta^*_\alpha\epsilon_{\mu\nu\rho\sigma}\Big\{-\left[\left((p+k)^\rho - \frac{M_B^2 - M_{D^*}^2}{q^2}q^\rho\right)g^{\alpha\sigma} + \frac{2}{q^2}p^\alpha p^\rho k^\sigma\right]T_1(q^2)$$
$$\left(\frac{2}{q^2}p^\alpha p^\rho k^\sigma - \frac{M_B^2 - M_{D^*}^2}{q^2}q^\rho g^{\alpha\sigma}\right)T_2(q^2) + \frac{2}{M_B^2 - M_{D^*}^2}p^\alpha p^\rho k^\sigma T_3(q^2)\Big\}\,.$$

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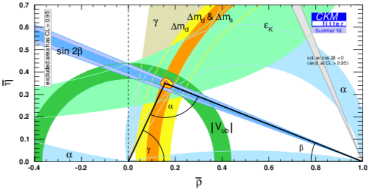

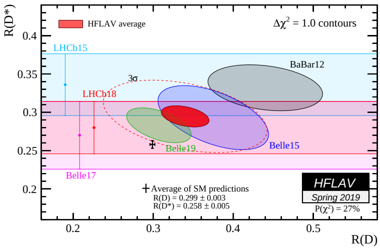

- SM assumption affects extraction of $|V_{cb}|$ and $R(D^{(*)})$ predictions

aim: remove dependence on experimental data in SM predictions

Available theory constraints (overview)

ordered from most stringent to least stringent

- lattice QCD [HPQCD, FNAL/MILC]
- QCD light-cone sum rules (LCSRs) [Gubernari,Kokulu,DvD ’18, Bordone et al. ’19]
- QCD three-point sum rules [Ligeti,Neubert,Nir ’92+’92]

ordered from most stringent to least stringent

- lattice QCD [HPQCD, FNAL/MILC]
  - for two out of three $\bar{B} \to D$ form factors for the physical q^2 range
  - for one out of seven $\bar{B} \to D^*$ form factor and only in one q^2 point
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  - NEW ! for all $\bar{B}_{(s)} \to D^{(*)}_{(s)}$ form factors, but only at $q^2 \leq 0$
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  - for some matrix elements (to be explained!) emerging in all $\bar{B}_{(s)} \to D^*_{(s)}$ form factors, but limited to one q^2 point

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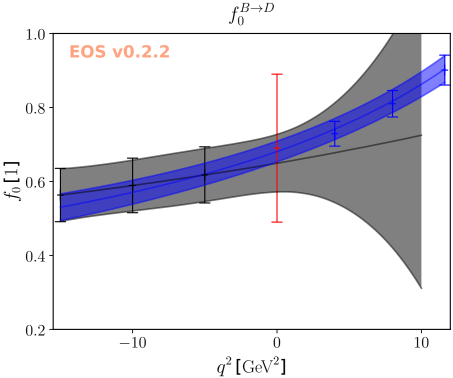
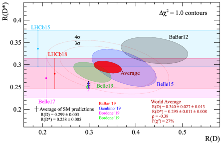
- eagerly awaiting results by FNAL/MILC on $\overline{B} \to D^*$ for the full (or at least a large part of) the q^2 range!





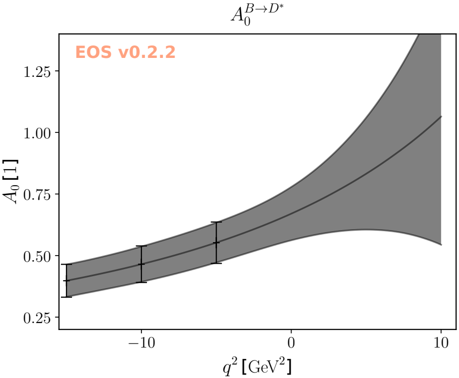
LCSR '18 only

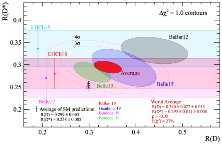
LCSR '18 + Lattice

LCSR '08

- for f_+ and f_0, good agreement between both approaches

Available theory constraints (plots)





LCSR ’18 only

LCSR ’18 + Lattice

LCSR ’08

- for f_+ and f_0, good agreement between both approaches
- for A_0, this is the first and only QCD-based determination at non-maximal q^2
- large uncertainties in LCSRs, which can be reduced by using a parametrization that accounts for additional theory inputs: the heavy quark expansion

Heavy-Quark Expansion to $1/m_c^2$

- any $\overline{B}^{(*)} \to D^{(*)}$ form factor h can be expanded in α_s, $\varepsilon_b \equiv \Lambda/m_b$, and $\varepsilon_c \equiv \Lambda/m_c$

$$h(w) = \xi(w)\hat{h}(w) = \boxed{\xi(w)}\Big(a + \hat{\alpha}_s b + \varepsilon_b\, c_b^{(i)}\, \Big[\boxed{\hat{L}_i(w)}\Big] + \varepsilon_c\, c_c^{(i)}\, \Big[\boxed{\hat{L}_i(w)}\Big] + \varepsilon_c^2\, d^{(i)}\, \Big[\boxed{\hat{\ell}_i(w)}\Big]\Big)$$

using $q^2 = M_B^2 + M_D^2 - 2M_B M_D w$

- adopting the power-counting $\varepsilon_b \sim \varepsilon_c^2 \sim \varepsilon^2$ on encounters
  - one function ξ at leading power in ε [Isgur,Wise '90]
  - three independent functions $\vec{L} \sim \{\chi_2, \chi_3, \eta\}$ at ε^1 [Falk,Neubert '92]
  - six independent functions $\vec{\ell} = \{\ell_1, \ldots, \ell_6\}$ at ε^2 [Falk,Neubert '92]
- common to expand these function in a new variable z with $|z| \ll 1$
- QCD three-point sum rules constrain χ_2, χ_3, η at $w = w_{\text{min}}$

Heavy-Quark Expansion to $1/m_c^2$

- any $\overline{B}^{(*)} \to D^{(*)}$ form factor h can be expanded in α_s, $\varepsilon_b \equiv \Lambda/m_b$, and $\varepsilon_c \equiv \Lambda/m_c$

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using $q^2 = M_B^2 + M_D^2 - 2M_B M_D w$

NEW !

analysis incl. all ε_c^2 terms with *a posteriori* comparisons of the fit models [Bordone, Jung, DvD '19]

- model $k/l/m$ expands ξ to kth order, $\chi_{2,3}$ and η to lth order, and $\ell_{1,\ldots,6}$ to mth order in $z(w)$
- minimal viable model is $2/1/0$ #par $= 13 + 13$
- use $3/2/1$ model to account for systematic uncertainties, increasing each order by one above the minimally viable model #par $= 23 + 23$

NEW !

assuming linear $SU(3)_F$ breaking $\ell_i^{(s)} = \ell_i^{(u,d)} + \varepsilon_F \delta_i$

- $\varepsilon_F \sim \varepsilon_c \sim \varepsilon$ leaves breaking terms beyond accuracy of the ansatz
- reduces number of free parameter #par $\to 34$

Dispersive bounds

- causality and unitarity of the S matrix implies form factors are complex-valued functions on entire complex q^2 plane
  - dyn. singularities in the q^2 plane are assoc. with phys. features:
    - poles are associated with $\bar{c}b$ bound states
    - branch cuts are associated with production 2-body (e.g. BD) and many-body production thresholds
  - dispersive bounds arise from a carefully constructed two-point function with computable normalization [Boyd,Grinstein,Lebed '95]
  - the bounds can be expressed through the parameters of the heavy-quark expansion [Caprini, Lellouch, Neubert '97]

NEW ! updated bounds to include parameters up to ε^2 [Bordone, Jung, DvD '19]

NEW ! expanded analysis to include both $\overline{B} \to D^{(*)}$ and $\overline{B}_s \to D_s^{(*)}$ form factors simultaneously and without assumption of $SU(3)_F$ symmetry [Bordone, Gubernari, Jung, DvD '19]

- update SM Predictions for $\overline{B}_q \to D_q^{(*)}\tau^-\overline{\nu}$
  - using only theory inputs [Bordone,Gubernari,Jung,DvD '19]

$$R_D = 0.2989 \pm 0.0032 \qquad R_{D_s} = 0.2970 \pm 0.0034$$
$$R_{D^*} = 0.2472 \pm 0.0050 \qquad R_{D_s^*} = 0.2450 \pm 0.0082$$

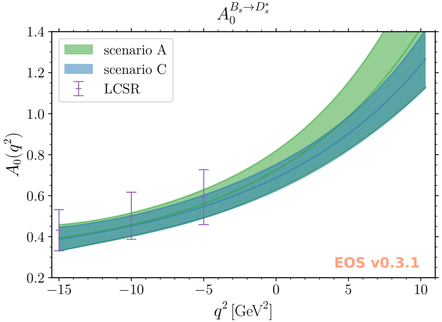
  - using theory + Belle measurements of e^-, μ^- final states

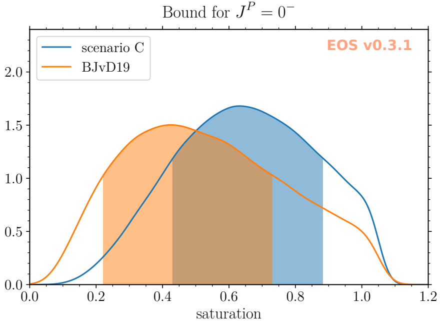
[Bordone,Gubernari,Jung,DvD '19]

$$R_D = 0.2981 \pm 0.0029 \qquad R_{D_s} = 0.2971 \pm 0.0034$$
$$R_{D^*} = 0.2504 \pm 0.0026 \qquad R_{D_s^*} = 0.2472 \pm 0.0077$$

- combined significance of R_D and R_{D^*} measurement now above 4σ

- gaussian constraint on the BGL form factor coefficients available as machine-readable files

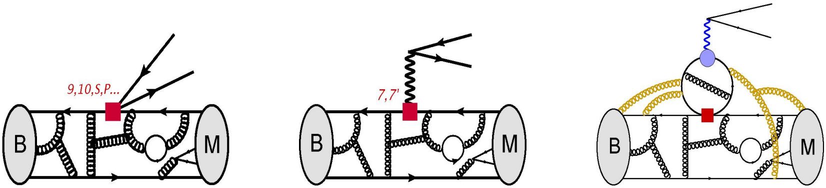




- using information on $\overline{B}_s \to D_s^{(*)}$ form factors in the heavy-quark expansion and the dispersive bounds has become essential for accurate determination of $\overline{B} \to D^{(*)}$ form factors

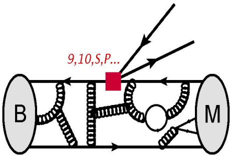
Non-local matrix elements in $\overline{B} \to \overline{K}^* \ell^+ \ell^-$

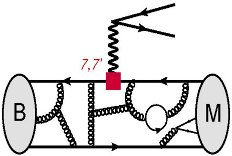
Amplitudes for $\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$

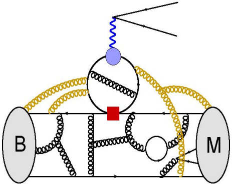


$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- non-local : $\mathcal{H}_\lambda(q^2) = i\mathcal{P}_\mu^\lambda \int d^4x \, e^{iq\cdot x} \, \langle \overline{M}_\lambda(k) | \, T\{\mathcal{J}_{\text{em}}^\mu(x), \mathcal{C}_i \mathcal{O}_i(0)\} \, |\overline{B}(q+k)\rangle$
    - major source of systematic uncertainty
    - several approaches dependent on the phase space region (i.e.: q^2)
    - here: only discuss impact of four-quark operators $\mathcal{O}_{1c}$ and $\mathcal{O}_{2c}$







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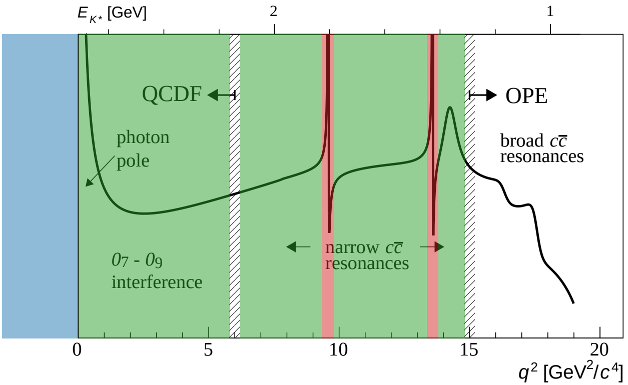
  below the J/ψ: Light-Cone OPE [Khodjamirian, Mannel, Pivovarov, Wang '10]

  - leading (local) terms. in QCD Factorization [Beneke, Feldmann, Seidel '01&'04]
  - subleading terms from LCSRs [Khodjamirian, Mannel, Pivovarov, Wang '10]

Regions of phase space



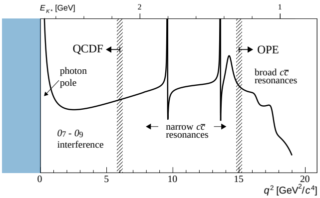
[sketch from Blake, Gershon, Hiller 1501.03309]

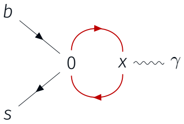
- accessible in light-cone OPE
- needed here for phenomenology
- (partially) constrained from data on $\bar{B} \to \bar{K}^{(*)}\psi_n$

Ansatz: parametrize, expand in small variable z as for local form factors, fit to theory and experimenta, and interpolate in central region

$$4m_c^2 - q^2 \gg \Lambda^2_{\text{hadr.}}$$

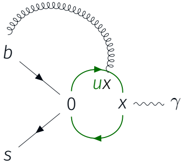
- expansion in operators at light-like distances $x^2 \simeq 0$ [Khodjamirian, Mannel, Pivovarov, Wang 2010]
- employing light-cone expansion of charm propagator [Balitsky, Braun 1989]





$$\xrightarrow{4m_c^2 - q^2 \gg \Lambda^2_{\text{hadr.}}} \underbrace{\left(\frac{C_1}{3} + C_2\right) C_{\text{LP}}(q^2)}_{\text{coeff \#1}} [\bar{s}\,\Gamma^\mu\, b] + \cdots$$

$$+ \underbrace{C_1 C^{\mu\rho\alpha\beta}_{\text{NLP}}(q^2;\omega_2)}_{\text{coeff \#2}} \times [\bar{s}_L \gamma_\rho \delta(\omega_2) \tilde{G}_{\alpha\beta} b_L]$$



$$0 \leq u \leq 1$$

w.i.p.

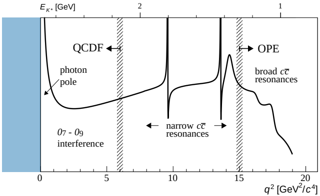
independently confirm result for C_{NLP}

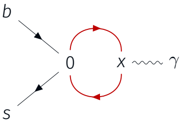
[Gubernari,DvD,Virto w.i.p.]

Light-Cone OPE, matching, and matrix elements

$$4m_c^2 - q^2 \gg \Lambda_{\text{hadr.}}^2$$

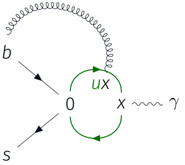
- expansion in operators at light-like distances $x^2 \simeq 0$ [Khodjamirian, Mannel, Pivovarov, Wang 2010]
- employing light-cone expansion of charm propagator [Balitsky, Braun 1989]





$$\mathcal{H}_\lambda = \text{coeff \#1} \times \mathcal{F}_\lambda + \mathcal{H}_\lambda^{\text{spect.}}$$
$$+ \text{coeff \#2} \otimes \mathcal{F}_\lambda^{\text{soft}}$$

- leading part identical to QCD Fact. results [Beneke, Feldmann, Seidel '01&'04]

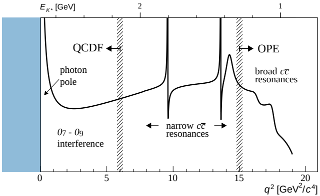


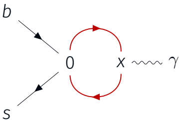
$$0 \leq u \leq 1$$

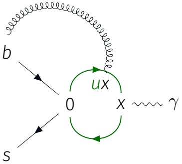
- subleading matrix element $\mathcal{F}_\lambda^{\text{soft}}$ can be estimated using B-LCSRs, starting with three-particle B distribution amplitudes (DA) [Khodjamirian, Mannel, Pivovarov, Wang '10]
- mistake in definition of DAs used for this purpose [e.g. Braun et al. '17]

$$4m_c^2 - q^2 \gg \Lambda_{\text{hadr.}}^2$$

- expansion in operators at light-like distances $x^2 \simeq 0$ [Khodjamirian, Mannel, Pivovarov, Wang 2010]
- employing light-cone expansion of charm propagator [Balitsky, Braun 1989]







$0 \leq u \leq 1$

w.i.p.

updating B-LCSR calculation of the matrix element of $\mathcal{F}_\lambda^{\text{soft}}$ [Gubernari,DvD,Virto w.i.p.]

w.i.p.

PRELIMINARY at $q^2 = 1\,\text{GeV}^2$ we find suppression by two orders of magnitude

- one from updated numerical inputs
- one from cancellations between “new” and “old” LCDAs

Dispersive bounds of the z parametrization

$$\mathcal{H} \propto \text{poles} \times \text{phase space} \times \left[\sum_k \alpha_k z^k\right] \qquad \sum_k |\alpha_k|^2 \leq 1$$

- BGL-like z parametrization useful due to dispersive bound on coefficients α_k for *local form factors*
- for *non-local matrix elements* formulating the dispersive bound is more complicated than for local form factors

w.i.p.

PRELIMINARY able to formulate bound [Gubernari,DvD,Virto w.i.p.]

- non-diagonal in coefficients, similar to situation for $B \to \pi$ form factor [Bourelly,Caprini,Lellouch '08]
- analytic results not cross checked yet in time for this conference

w.i.p.

existence of the bound implies homogeneous convergence of the parametrization

- systematic uncertainties due to cut-off of series expansion are bounded!

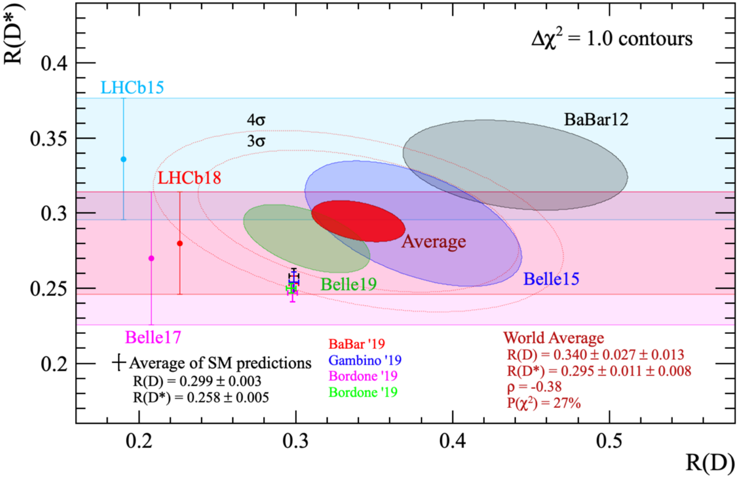
Summary

Summary

- tensions between theory predictions and experimental results demand heightend scrutiny of all results
  - here: revisiting hadronic matrix elements needed for the theory predictions; Needs to understand old physics first!
- Form factors in $\overline{B}_q \to D_q^{(*)} \ell^- \overline{\nu}$
  - NEW! simultaneous analysis of theory and exp. constraints within heavy-quark expansion to $1/m_c^2$
  - $b \to c\tau\overline{\nu}$ LFU SM predictions slightly lowered when incl. $1/m_c^2$ effects, increasing tension w.r.t. measurements to $\geq 4\sigma$
  - tension in V_{cb} puzzle reduced, but not entirely removed
- Non-local matrix elements in $\overline{B} \to \overline{K}^* \ell^+ \ell^-$
  - w.i.p. independent check of next-to-leading power coefficient ✓
  - w.i.p. update of matrix elements at next-to-leading power, reduction in size by at least one order of magnitude
  - w.i.p. formulating dispersive bound, thereby providing handle on systematic uncertainties arising from cut-off of the series expansion

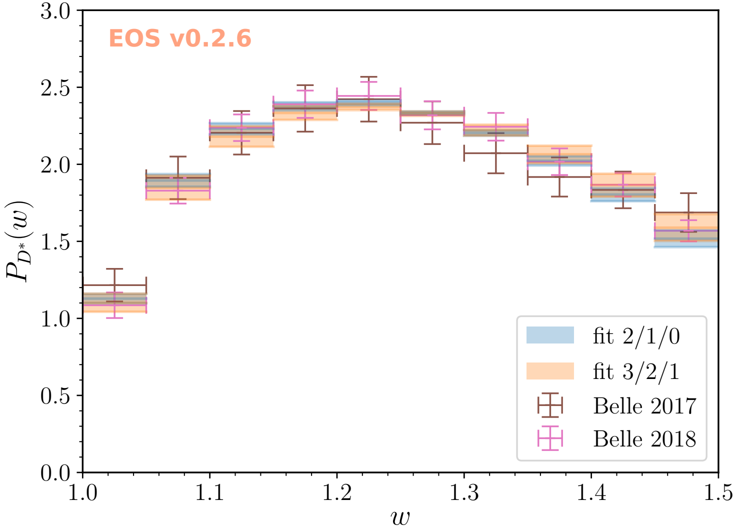
Backup Slides

R_D and R_{D^*}



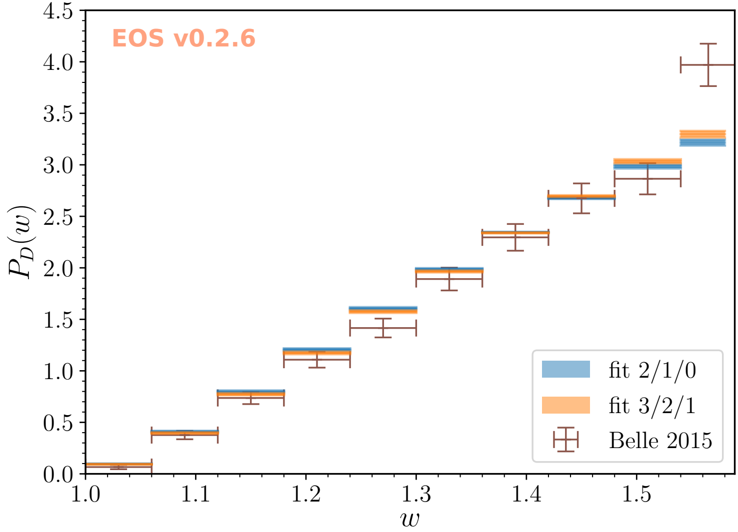
[M. Rotondo for upcoming HFLAV update]

Challenging data of $\overline{B} \to D^{(*)}\ell^-\overline{\nu}$ decay



$$P \equiv \frac{1}{\Gamma}\frac{d\Gamma}{dw} \qquad q^2 = M_B^2 + M_{D^{(*)}}^2 - 2M_B M_{D^{(*)}} w$$

Challenging data of $\overline{B} \to D^{(*)}\ell^-\overline{\nu}$ decay



$$P \equiv \frac{1}{\Gamma}\frac{d\Gamma}{dw} \qquad q^2 = M_B^2 + M_{D^{(*)}}^2 - 2M_B M_{D^{(*)}} w$$

Threshold setting

[Gubernari,Kokulu,DvD '18]

- LCSRs can be expressed as integrals over OPE result for the two-point function
- schematically

$$F(q^2; M^2) \sim \int_0^{\sigma_0} ds \; \exp[-(s - M_D^2)/M^2] \, \rho(s)$$

M^2: Borel-conjugate to the final state mass square k^2

- commonly, the threshold σ_0 is determined from further sum rules

[Khodjamirian et al. '05, '06, '08]

- here, we determine the threshold by imposing that the dependence on M^2 reproduces the final state mass (i.e. $M_{D^{(*)}}$):

$$M_D^2 = \frac{1}{F(q^2; M^2)} \frac{\partial F(q^2; M^2)}{\partial(-1/M^2)}$$

Goodness of Fit

likelihood	#obs \ #par	2/1/0	3/2/1	3/2/1	3/2/1	3/2/1
		13	23	23	23	23
lattice(D)	12	11.15	7.06	7.29	7.29	7.36
lattice(D^*)	1	0.00	0.01	0.00	0.01	0.00
QCDSR	5	4.58	0.04	0.04	0.01	0.02
LCSR	33	7.14	2.79	3.23	3.14	2.98
$\overline{B} \to D\{e^-, \mu^-\}\overline{\nu}$	(9)	—	—	—	—	6.75
$\overline{B} \to D^*\{e^-, \mu^-\}\overline{\nu}$ 2017	(9)	—	—	6.95	—	8.04
$\overline{B} \to D^*\{e^-, \mu^-\}\overline{\nu}$ 2018	(9)	—	—	—	4.42	4.84
	51	22.87	9.91	—	—	—
total	(60)	—	—	17.51	14.88	—
	(78)	—	—	—	—	30.00

Determination of $|V_{cb}|$ from Exclusive B Decays

- express all exclusive branching ratios $\mathcal{B}^{(*)}$ as $\overline{B}^0 \to D^{(*),+}\ell^-\overline{\nu}$
- predict correlated $\mathcal{B}/|V_{cb}|^2$ and $\mathcal{B}^*/|V_{cb}|^2$, and extract V_{cb} from the world averages

[ALEPH, BaBar, Belle, CLEO2, Delphi, OPAL]

	scenarios				
model	2/1/0	3/2/1	3/2/1	3/2/1	3/2/1
exp. likelihood	—	—	2017	2018	all exp.
$\mathcal{B}(\overline{B}^0 \to D^+\{e^-,\mu^-\}\overline{\nu})/\|V_{cb}\|^2$	12.99 ± 0.35	13.48 ± 0.37	—	—	13.56 ± 0.35
$\mathcal{B}(\overline{B}^0 \to D^{*+}\{e^-,\mu^-\}\overline{\nu}/\|V_{cb}\|^2$	32.33 ± 1.28	33.16 ± 2.15	31.74 ± 1.46	32.19 ± 1.03	32.00 ± 1.03
correlation	0.34	0.14	—	—	0.10
$\|V_{cb}\| \times 10^3$ from $\overline{B} \to D\{e^-,\mu^-\}\overline{\nu}$	41.5 ± 1.2	40.7 ± 1.2	—	—	40.6 ± 1.1
$\|V_{cb}\| \times 10^3$ from $\overline{B} \to D^*\{e^-,\mu^-\}\overline{\nu}$	39.8 ± 1.2	39.3 ± 1.7	40.1 ± 1.3	39.8 ± 1.0	40.0 ± 1.1
	—	—	(39.5 ± 1.9)	(39.0 ± 1.3)	—
$\|V_{cb}\| \times 10^3$ combined incl. corr.	40.7 ± 1.0	40.2 ± 1.0	—	—	40.3 ± 0.8

form factor inputs: theory only, theory + Belle spectra

- compatible with *inclusive* det. $|V_{cb}| = (42.00 \pm 0.64) \times 10^{-3}$ at 1.2σ
- average of exclusive and inclusive det. $|V_{cb}| = (41.3 \pm 0.5) \times 10^{-3}$