A puzzle in $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction

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Based on
arXiv:2007.10338
in collaboration with
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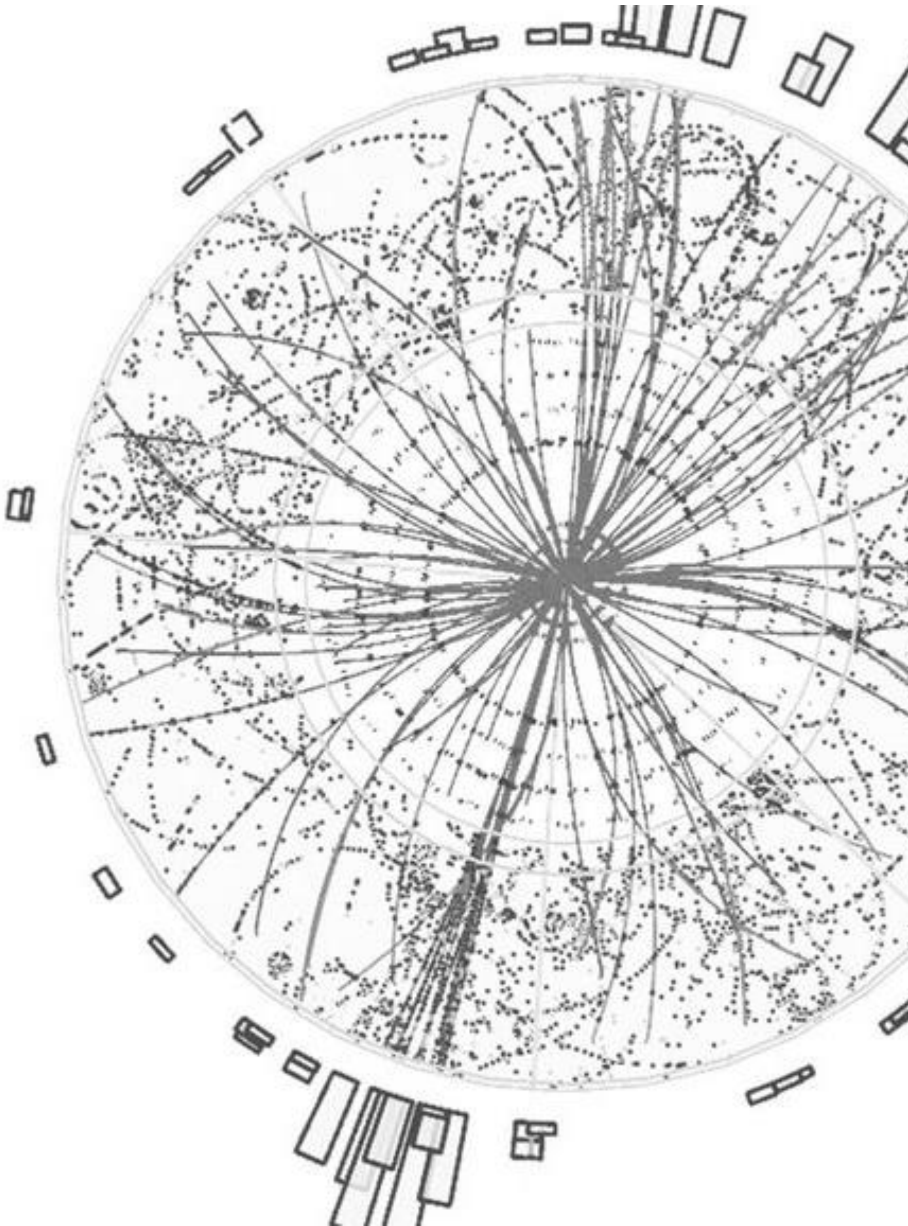
Talk outline



Introduction

- f_s/f_d fragmentation fraction

Method

- QCD factorization
- Light-cone sum rules (LCSRs)

Results for $\bar{B}^0_{(s)} \to D^+_{(s)}\{\pi^-, K^-\}$

- f_s/f_d fragmentation fraction
- A new puzzle: tension with experimental data

Possible explanations of the Puzzle

- large NLP corrections
- BSM effects

Introduction

Fragmentation fraction f_s/f_d

fragmentation fraction f_s/f_d: quantifies the relative production rate of B_s^0 with respect to B^0 mesons

essential input to study B_s^0 decays at LHC
e.g. $B_s^0 \to \mu^+\mu^-$ important probes for BSM physics

branching fractions in B^0 and B^+ decays measured very precisely a B-factories
but B-factories do not produce (enough) B_s mesons!

determine this ratio using [Fleischer/Serra/Tuning '11]

$$\frac{f_s}{f_d} = \frac{\mathcal{B}(B^0 \to D^-K^+)}{\mathcal{B}(B_s^0 \to D_s^-\pi^+)} \frac{\epsilon_{DK}}{\epsilon_{D_s\pi}} \frac{N_{D_s\pi}}{N_{DK}}$$

ϵ efficiencies, N signal yield

can also be predicted using semileptonic decays [LHCb '11 arXiv:1111.2357]

Effective Lagrangian

advantage in considering $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$ decays (all quark flavours different in the final state) respect to, e.g. $\bar{B}^0 \to D^{(*)+}\pi^-$

$$\Downarrow$$

clean theoretical predictions: no weak annihilation or penguin topologies, no chirally enhanced hard-scattering contributions

effective Lagrangian

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} V_{cb} V_{uq_2}^* \left(C_1 O_1^{q_2} + C_2 O_2^{q_2} \right) \qquad q_2 = d, s$$

effective operators

$$O_1^{q_2} = (\bar{c}\gamma^\mu P_L T^A b)\left(\bar{q}_2 \gamma_\mu P_L T^A u\right) \qquad O_2^{q_2} = (\bar{c}\gamma^\mu P_L b)\left(\bar{q}_2 \gamma_\mu P_L u\right)$$

Wilson coefficients q_2-flavour universal in the SM, BSM effects may not q_2-flavour universal

Naïve factorization

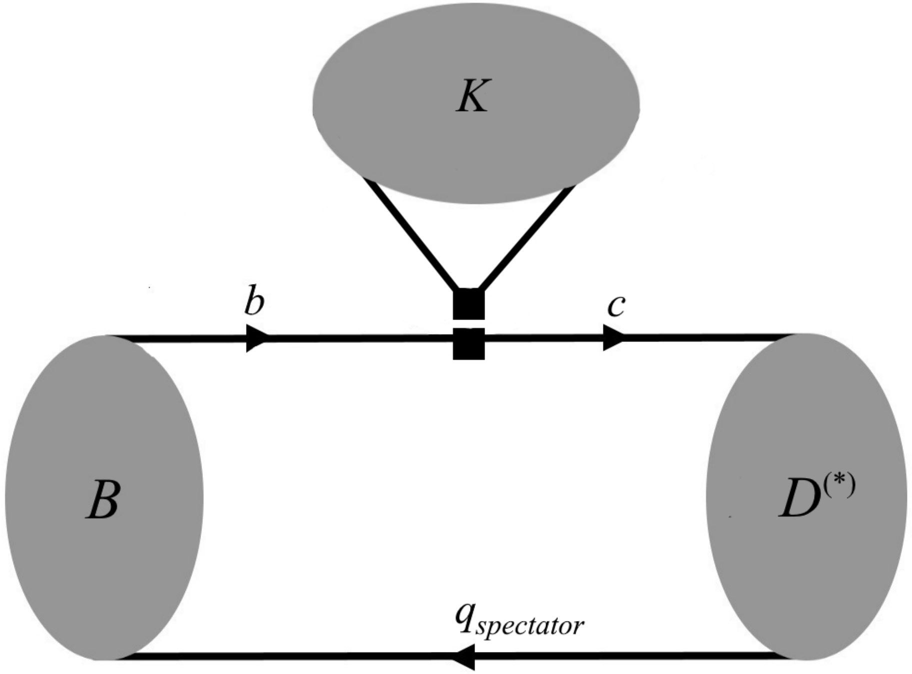
decompose a very complicated matrix element — e.g. $\langle D^+K^-|O_i|\bar{B}_s^0\rangle$ — into simpler matrix elements

naïve factorization:

$$\langle D^+K^-|O_i|\bar{B}_s^0\rangle = \langle K^-|j_a|0\rangle\langle D^+|j_b|\bar{B}_s^0\rangle + O(\alpha_s) + O\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)$$

$\langle K^-|j_a|0\rangle \propto$ decay constant

$\langle D^+|j_b|\bar{B}_s^0\rangle \propto B \to D$ form factors $F_j^{B\to D}$



QCD factorization

compute systematically α_s corrections, neglect power corrections $\frac{\Lambda_{\mathrm{QCD}}}{m_b}$

[Beneke/Buchalla/Neubert/Sachrajda ’00]

for M_1 and M_2 both light

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \sum_j F_j^{B\to M_1}(m_2^2) \int_0^1 du\, T_{ij}^I(u) \Phi_{M_2}(u) \; + (M_1 \leftrightarrow M_2)$$
$$+ \int_0^1 d\xi du dv\, T_i^{II}(\xi, u, v) \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u)$$

for M_1 heavy, and M_2 light

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \sum_j F_j^{B\to M_1}(m_2^2) \int_0^1 du\, T_{ij}^I(u) \Phi_{M_2}(u)$$

$T_{ij}^I(u)$ computed at NNLO in α_s

[Huber/Kränkl/Li ’16]

Our theoretical predictions

improve theoretical predictions for $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$ branching fractions

use QCD factorization (leading power in $\frac{\Lambda_{\text{QCD}}}{m_b}$)

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+K^-)} = \frac{\tau_{B_s}}{\tau_{B_d}} \left|\frac{V_{ud}}{V_{us}}\right|^2 \frac{f_\pi^2}{f_K^2} \left|\frac{F_0^{B_s\to D_s}(M_\pi^2)}{F_0^{B\to D}(M_K^2)}\right| \left|\frac{a_1(D_s^+\pi^-)}{a_1(D^+K^-)}\right|^2 \times kin.\ factots$$

- Wilson coefficients a_1 computed in Huber/Kränkl/Li '16
- update $B \to D^{(*)}$ and $B_s \to D_s^{(*)}$ form factors [Bordone/NG/Jung/van Dyk '19]
- estimate $\frac{\Lambda_{\text{QCD}}}{m_b}$ corrections **for the first time**

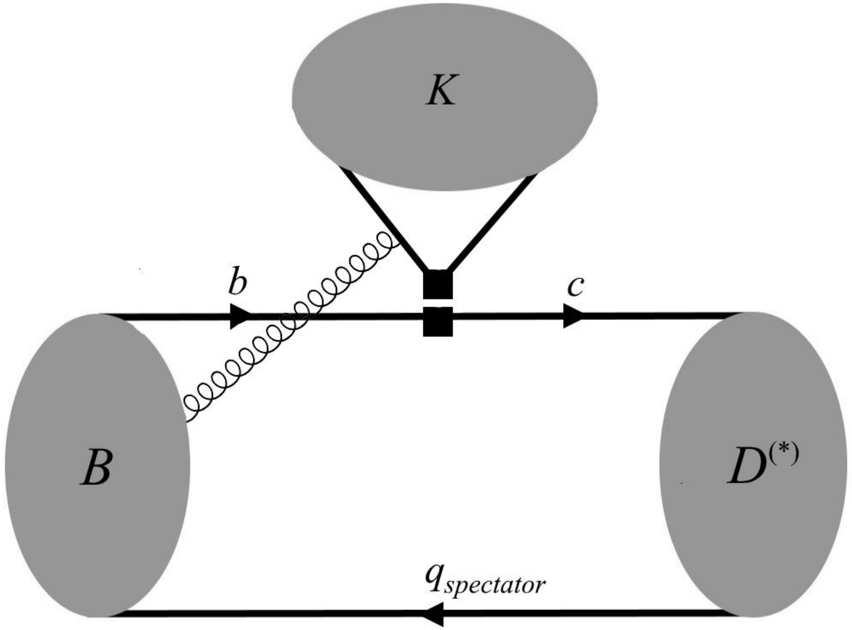
Power corrections

1. use form factors in terms of the QCD fields $\Longrightarrow$ no $\frac{\Lambda_{\mathrm{QCD}}}{m_c}$ corrections

2. hard-gluon between b or c quarks and the light meson is included in the WC

3. no hard-collinear gluon between spectator quark and the light meson (spectator is soft)

4. soft-gluon exchange between the $\bar{B}^0_{(s)}D^{(*)+}_{(s)}$ system and the light meson L
   we estimate this contribution
   with light-cone sum rules (LCSRs)



Power corrections estimation

Light-cone sum rules in a nutshell

light-cone sum rules (LCSRs) are a method to calculate hadronic matrix elements

method based on:

- dispersion relation
- quark-hadron duality
- light-cone OPE

method already applied in Khodjamirian et al 2010 for nonlocal matrix elements in $B \to K^{(*)}$

use a similar set-up

we apply this method for the first time to estimate $\mathcal{A}\left(\bar{B}_q^0 \to D_q^{(*)+} L^-\right)\Big|_{\mathrm{NLP}}$

Light-cone sum rules results

our conservative estimates

$$\frac{\mathcal{A}(\bar{B}_q^0 \to D_q^+ L^-)\big|_{\text{NLP}}}{\mathcal{A}(\bar{B}_q^0 \to D_q^+ L^-)\big|_{\text{LP}}} \simeq [0.06, 0.6]\%$$

$$\frac{\mathcal{A}(\bar{B}_q^0 \to D_q^{*+} L^-)\big|_{\text{NLP}}}{\mathcal{A}(\bar{B}_q^0 \to D_q^{*+} L^-)\big|_{\text{LP}}} \simeq [0.04, 0.4]\%$$

lower bound correspond to our **central value**
upper bound obtained increasing the central value by a **factor of 10**
motivated by the large uncertainties on λ_E^2 and λ_H^2

corroborate the fact that $\boldsymbol{\bar{B}_q^0} \to \boldsymbol{D_q^{(*)+} L^-}$ decays are theoretically clean

Numerical inputs and results

Form factors in HQE

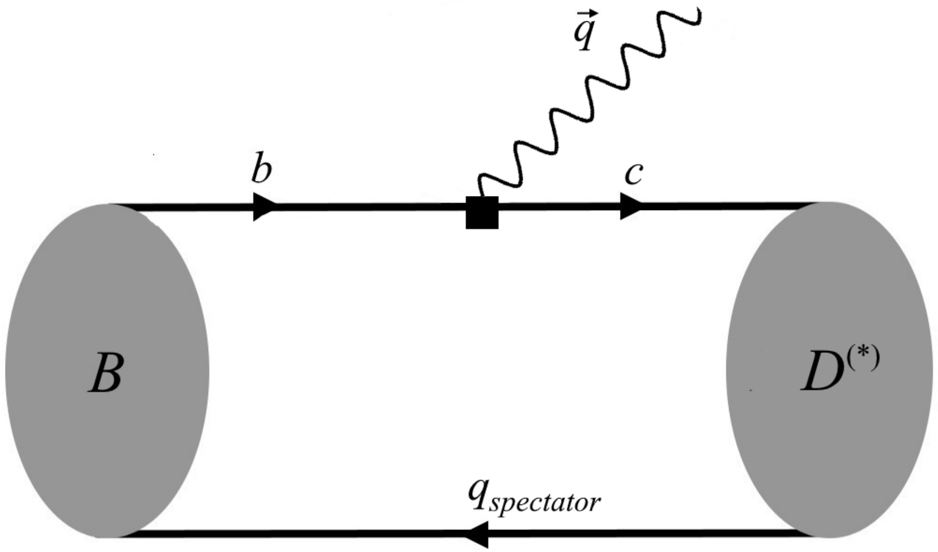
expand $B \to D^{(*)}$ FFs in the limit $m_{b,c} \to \infty$

$$F^{B\to D^{(*)}}(q^2) = c_0\xi(q^2) + c_1\frac{\alpha_s}{\pi}C_i(q^2) + c_2\frac{1}{m_b}L_i(q^2) + c_3\frac{1}{m_c}L_i(q^2) + c_4\frac{1}{m_c^2}l_i(q^2)$$

$$F^{B_s\to D_s^{(*)}}(q^2) = c_0\xi^s(q^2) + c_1\frac{\alpha_s}{\pi}C_i(q^2) + c_2\frac{1}{m_b}L_i^s(q^2) + c_3\frac{1}{m_c}L_i^s(q^2) + c_4\frac{1}{m_c^2}l_i(q^2)$$

include $1/m_c^2$ corrections [Bordone/Jung/van Dyk '19]

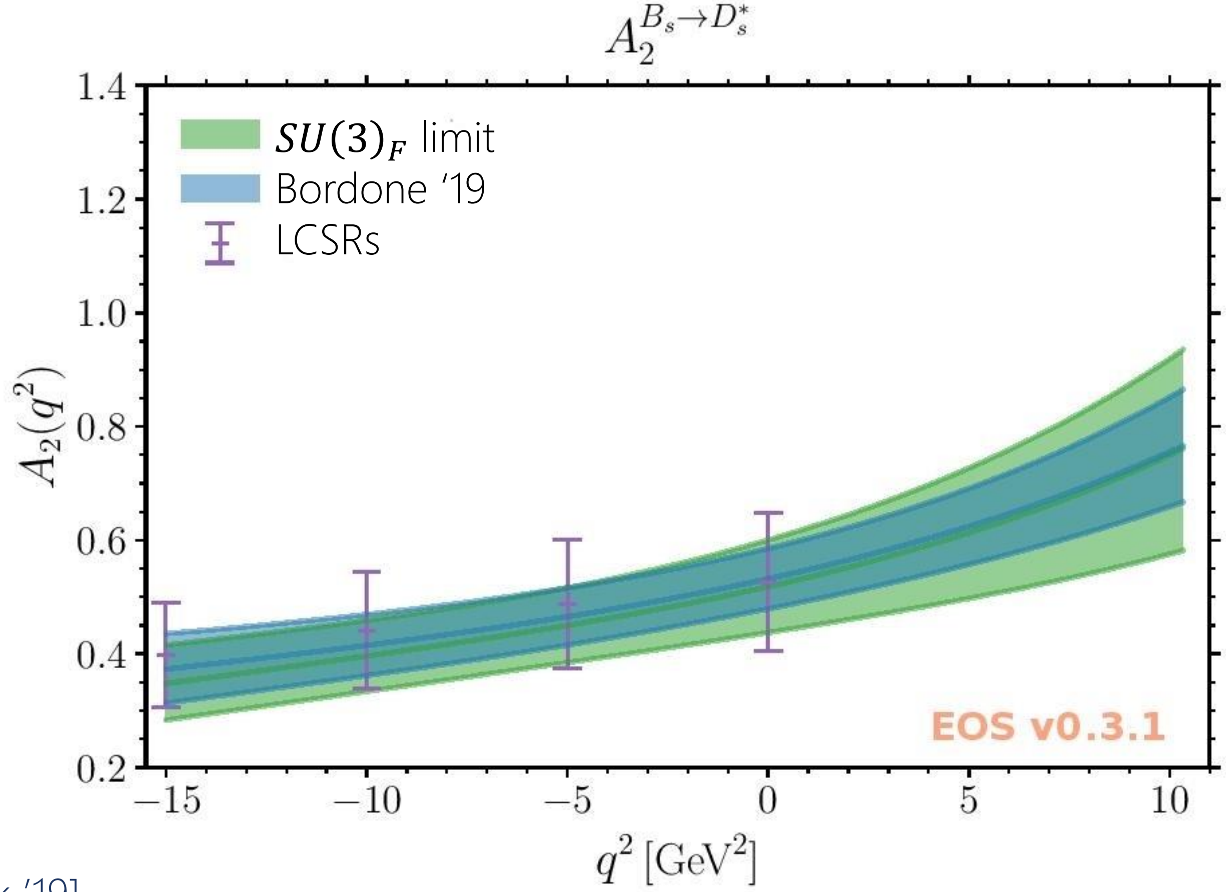
all $B \to D^{(*)}$ and $B_s \to D_s^{(*)}$ FFs parametrized in terms of 14 Isgur-Wise functions



Form factors predictions

constrain the **Isgur-Wise functions** combining

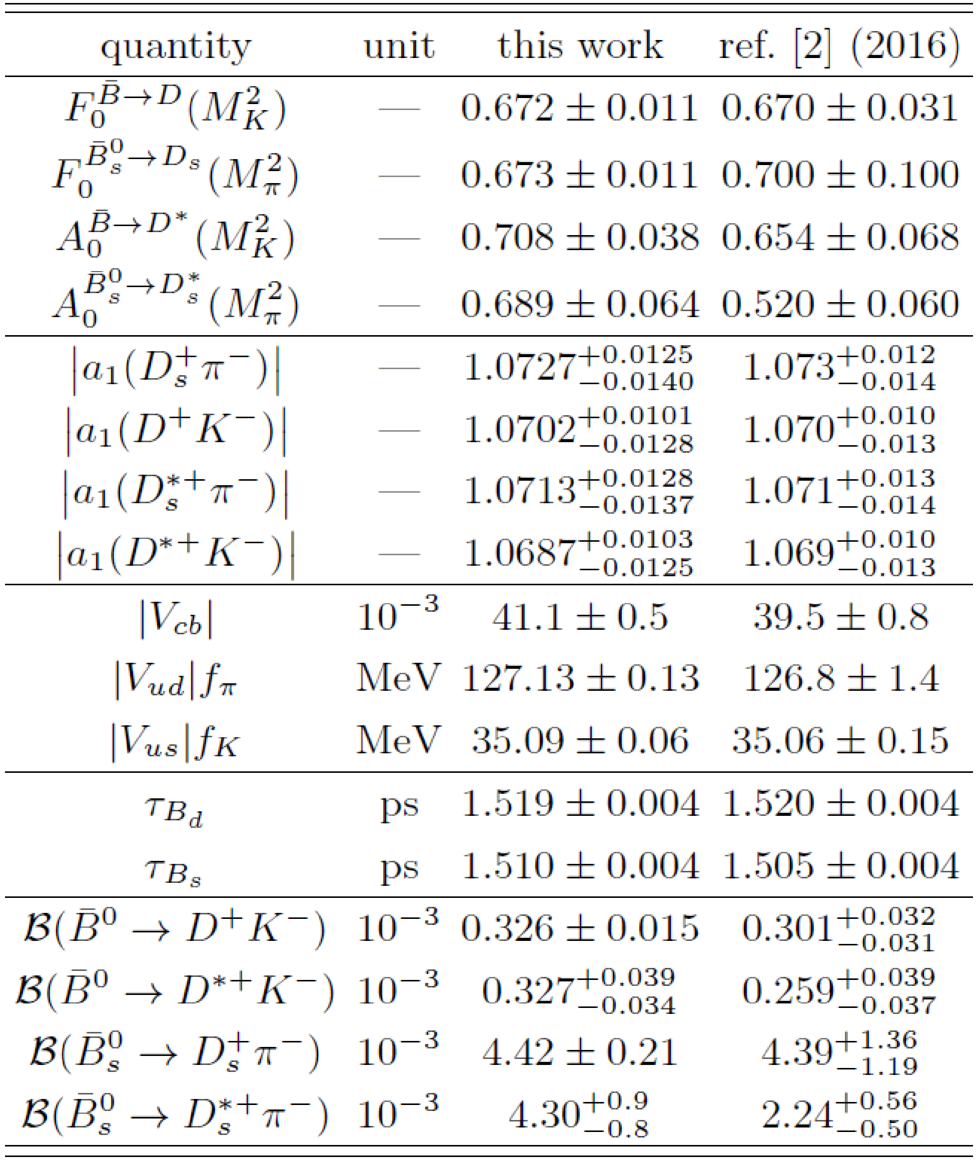
- lattice QCD (where available)
- light-cone sum rules for the FFs
- SVZ sum rules for Isgur-Wise functions
- dispersive bounds
- with and w/o exp data



results for all $B \to D^{(*)}$ FFs and $B_s \to D_s^{(*)}$ FFs
in the whole physical phase space

[Bordone/NG/Jung/van Dyk '19]

Numerical inputs and results



quantity	unit	this work	ref. [2] (2016)
$F_0^{\bar{B}\to D}(M_K^2)$	—	0.672 ± 0.011	0.670 ± 0.031
$F_0^{\bar{B}_s^0\to D_s}(M_\pi^2)$	—	0.673 ± 0.011	0.700 ± 0.100
$A_0^{\bar{B}\to D^*}(M_K^2)$	—	0.708 ± 0.038	0.654 ± 0.068
$A_0^{\bar{B}_s^0\to D_s^*}(M_\pi^2)$	—	0.689 ± 0.064	0.520 ± 0.060
$\lvert a_1(D_s^+\pi^-)\rvert$	—	$1.0727^{+0.0125}_{-0.0140}$	$1.073^{+0.012}_{-0.014}$
$\lvert a_1(D^+K^-)\rvert$	—	$1.0702^{+0.0101}_{-0.0128}$	$1.070^{+0.010}_{-0.013}$
$\lvert a_1(D_s^{*+}\pi^-)\rvert$	—	$1.0713^{+0.0128}_{-0.0137}$	$1.071^{+0.013}_{-0.014}$
$\lvert a_1(D^{*+}K^-)\rvert$	—	$1.0687^{+0.0103}_{-0.0125}$	$1.069^{+0.010}_{-0.013}$
$\lvert V_{cb}\rvert$	10^{-3}	41.1 ± 0.5	39.5 ± 0.8
$\lvert V_{ud}\rvert f_\pi$	MeV	127.13 ± 0.13	126.8 ± 1.4
$\lvert V_{us}\rvert f_K$	MeV	35.09 ± 0.06	35.06 ± 0.15
τ_{B_d}	ps	1.519 ± 0.004	1.520 ± 0.004
τ_{B_s}	ps	1.510 ± 0.004	1.505 ± 0.004
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	10^{-3}	0.326 ± 0.015	$0.301^{+0.032}_{-0.031}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	10^{-3}	$0.327^{+0.039}_{-0.034}$	$0.259^{+0.039}_{-0.037}$
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	10^{-3}	4.42 ± 0.21	$4.39^{+1.36}_{-1.19}$
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	10^{-3}	$4.30^{+0.9}_{-0.8}$	$2.24^{+0.56}_{-0.50}$

improved FFs uncertainties

same results for the WC of QCDF as in Huber/Kränkl/Li

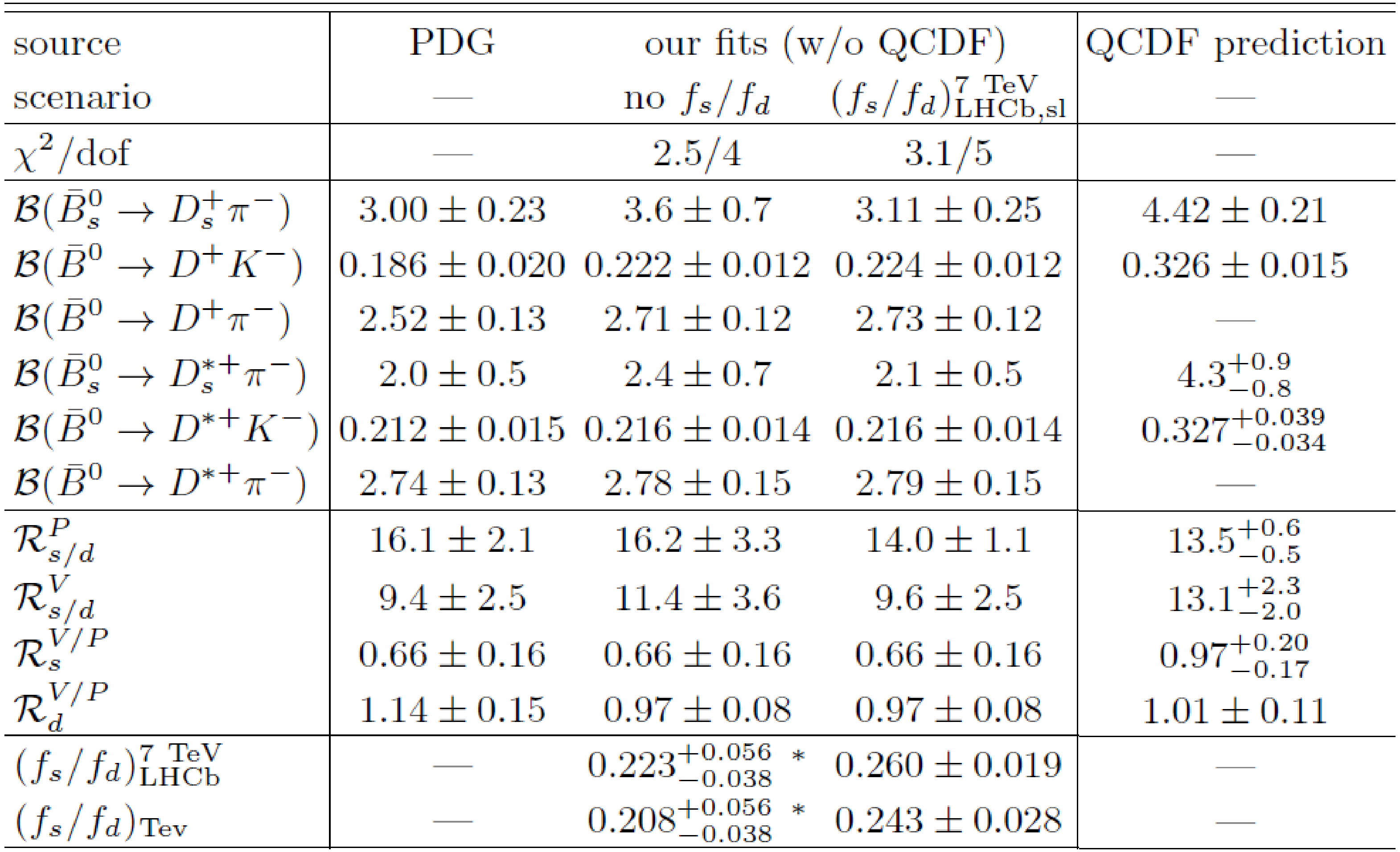
update remaining inputs

more precise predictions

unc. dominated by the FFs

Comparison with measurements

Fits to the available data



source	PDG	our fits (w/o QCDF)		QCDF prediction
scenario	—	no f_s/f_d	$(f_s/f_d)^{7\ \mathrm{TeV}}_{\mathrm{LHCb,sl}}$	—
χ^2/dof	—	$2.5/4$	$3.1/5$	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	—
$\mathcal{R}^P_{s/d}$	16.1 ± 2.1	16.2 ± 3.3	14.0 ± 1.1	$13.5^{+0.6}_{-0.5}$
$\mathcal{R}^V_{s/d}$	9.4 ± 2.5	11.4 ± 3.6	9.6 ± 2.5	$13.1^{+2.3}_{-2.0}$
$\mathcal{R}^{V/P}_s$	0.66 ± 0.16	0.66 ± 0.16	0.66 ± 0.16	$0.97^{+0.20}_{-0.17}$
$\mathcal{R}^{V/P}_d$	1.14 ± 0.15	0.97 ± 0.08	0.97 ± 0.08	1.01 ± 0.11
$(f_s/f_d)^{7\ \mathrm{TeV}}_{\mathrm{LHCb}}$	—	$0.223^{+0.056}_{-0.038}$ *	0.260 ± 0.019	—
$(f_s/f_d)_{\mathrm{Tev}}$	—	$0.208^{+0.056}_{-0.038}$ *	0.243 ± 0.028	—

- fits indicate that measurements are consistent

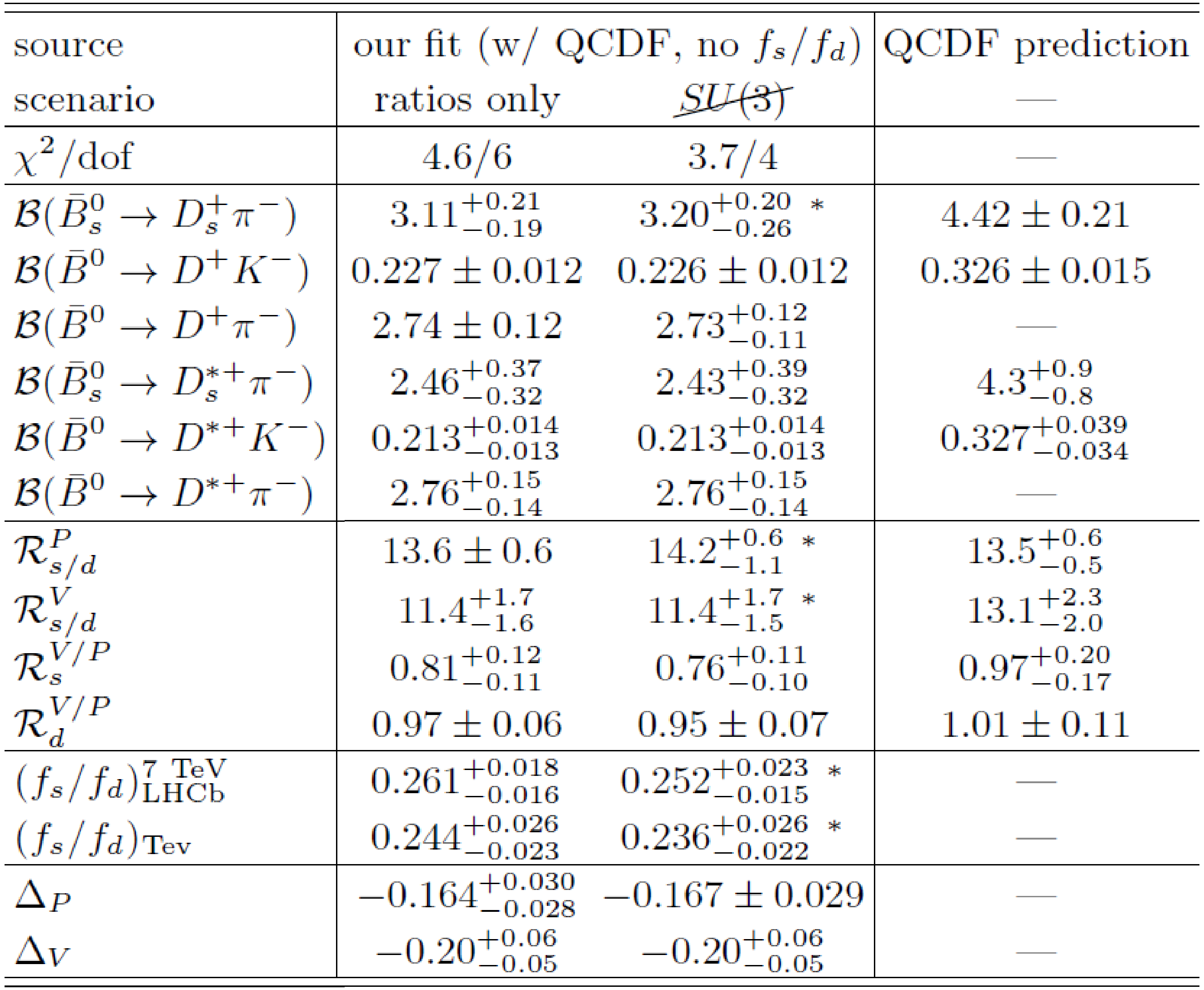
- discrepancy between measurements and theoretical predictions:

$\bar{B}_s^0 \to D_s^+\pi^- \quad \to 4\sigma$
$\bar{B}^0 \to D^+K^- \quad \to 5\sigma$
$\bar{B}_s^0 \to D_s^{*+}\pi^- \quad \to 2\sigma$
$\bar{B}^0 \to D^{*+}K^- \quad \to 3\sigma$

Possible explanations

1. large nonfactorizable contributions of $O(15-20\%)$ ⟶ excluded by our estimate at 4.4σ level (see also next slides)
2. experimental issue ⟶ would imply problems in several (consistent) measurements (CLEO, BaBar, LHCb, Belle)
3. shift in the inputs, larger uncertainties in V_{ud}, V_{us}, V_{cb} ⟶ would probably violate CKM unitarity
4. assuming that both theoretical and experimental results are correct ⟶ BSM physics only explanation left (see next slides)
5. a combination of the effects discussed above

Fit allowing large non-fact. contr.



source	our fit (w/ QCDF, no f_s/f_d)		QCDF prediction
scenario	ratios only	$\cancel{SU(3)}$	—
χ^2/dof	4.6/6	3.7/4	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	—
$\mathcal{R}_{s/d}^P$	13.6 ± 0.6	$14.2^{+0.6}_{-1.1}$ *	$13.5^{+0.6}_{-0.5}$
$\mathcal{R}_{s/d}^V$	$11.4^{+1.7}_{-1.6}$	$11.4^{+1.7}_{-1.5}$ *	$13.1^{+2.3}_{-2.0}$
$\mathcal{R}_s^{V/P}$	$0.81^{+0.12}_{-0.11}$	$0.76^{+0.11}_{-0.10}$	$0.97^{+0.20}_{-0.17}$
$\mathcal{R}_d^{V/P}$	0.97 ± 0.06	0.95 ± 0.07	1.01 ± 0.11
$(f_s/f_d)_{\mathrm{LHCb}}^{7\ \mathrm{TeV}}$	$0.261^{+0.018}_{-0.016}$	$0.252^{+0.023}_{-0.015}$ *	—
$(f_s/f_d)_{\mathrm{Tev}}$	$0.244^{+0.026}_{-0.023}$	$0.236^{+0.026}_{-0.022}$ *	—
Δ_P	$-0.164^{+0.030}_{-0.028}$	-0.167 ± 0.029	—
Δ_V	$-0.20^{+0.06}_{-0.05}$	$-0.20^{+0.06}_{-0.05}$	—

$$\frac{\mathcal{A}(\bar{B}^0 \to D^+K^-)}{\mathcal{A}(\bar{B}^0 \to D^+K^-)|_{\mathrm{LP}}} = 1 + \Delta_P$$

$$\frac{\mathcal{A}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathcal{A}(\bar{B}_s^0 \to D_s^+\pi^-)\big|_{\mathrm{LP}}} = 1 + r_{SU(3)}^P\,\Delta_P$$

$$\frac{\mathcal{A}(\bar{B}^0 \to D^{*+}K^-)}{\mathcal{A}(\bar{B}^0 \to D^{*+}K^-)|_{\mathrm{LP}}} = 1 + \Delta_V$$

$$\frac{\mathcal{A}(\bar{B}_s^0 \to D_s^{*+}\pi^-)}{\mathcal{A}(\bar{B}_s^0 \to D_s^{*+}\pi^-)\big|_{\mathrm{LP}}} = 1 + r_{SU(3)}^V\,\Delta_V$$

with $r_{SU(3)}^V \in [0.9, 1.1]$

consistent picture and improved determination of f_s/f_d

Is NP a viable option?

observe that our previous fits predict $\Delta_P = \Delta_V$

$$\Downarrow$$

implies BSM contributions to $\boldsymbol{C_{1,2}^{q_2}}$

for the moment being, we do not consider operator that do not contribute in the SM

we also assume that $\boldsymbol{C_{1,2}^{d}}$ and $\boldsymbol{C_{1,2}^{s}}$ have the same shift, consistently with our fit

implies $O(20\%)$ tree-level corrections in $b \to cu(d/s)$ transitions not observed so far

Consistency check

- compatible with the Γ_q (decay width of the B_q meson)
- lifetimes ratio τ_{B_s}/τ_{B_d} both predicted and measured to very high precision ⟶ main BSM contributions cancel in the ratio
- consistent with $\bar{B}^0 \to D^{(*)+}\pi^-$ and $\bar{B}_s^0 \to D_s^{(*)+}K^-$ branching fractions
  also in this case measurements < predictions

BSM viable hypothesis (?)

- Iguro/Kitahara arXiv:2008.01086
- Bordone/Greljo/Marzocca 2103.10332 (see Admir talk)

Conclusion and prospects

Prospects

- measure absolute branching fractions, especially for B_s mesons
- please produce more B_s mesons at Belle!

we suggest a two-staged approach to measure f_s/f_d

$$\frac{\mathcal{B}(\bar{B}^0 \to D^+K^-)}{\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)} = \frac{\mathcal{B}(\bar{B}^0 \to D^+K^-)}{\mathcal{B}(\bar{B} \ \to X)} \frac{\mathcal{B}(\bar{B} \ \to X)}{\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)}$$

for instance, $X = D^+\pi^-$ (larger branching fraction, cancel π syst. unc.)

$$\frac{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+K^-)} = 12.47^{+0.42}_{-0.37}$$

low experimental uncertainty

Summary and conclusion 1/2

revisit theoretical predictions of the $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$ branching fractions

$$\mathcal{A}(\bar{B}^0 \to D^+K^-) = 0.326 \pm 0.015$$

$$\mathcal{A}(\bar{B}_s^0 \to D_s^+\pi^-) = 4.42 \pm 0.21$$

$$\mathcal{A}(\bar{B}^0 \to D^{*+}K^-) = 0.327^{+0.039}_{-0.034}$$

$$\mathcal{A}(\bar{B}_s^0 \to D_s^{*+}\pi^-) = 4.3^{+0.9}_{-0.8}$$

updated values of the form factors

next-to-leading power effects included for the first time

extract f_s/f_d in various scenarios

Summary and conclusion 2/2

4.4σ discrepancy between theoretical predictions and measurements of the $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$ branching fractions

four possible (unsatisfactory) explanations

1. large nonfactorizable contributions of $O(15-20\%)$ ⟶ unlikely since these cays are well understood in QCDF, and contradict our estimates (factor of 50)
2. experimental issue $O(30\%)$ systematic shift ⟶ would invalidate most of the B meson branching fractions measurements
3. shift in the inputs (e.g. V_{ud}, V_{us}, V_{cb}) ⟶ would probably violate CKM unitarity
4. BSM physics effects ⟶ $O(20\%)$ tree-level corrections in $b \to cu(d/s)$ transitions not observed so far

Thank you!