A puzzle in $\bar{B}^0 \to D^{(*)+}K^-$ and $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ decays

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Based on
arXiv:2007.10338
in collaboration with
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Status and prospects
of non-leptonic B Decays
Siegen
31-May-2022

Particle Physics Phenomenology after the Higgs Discovery
Collaborative Research Center TRR 257

UNIVERSITÄT SIEGEN

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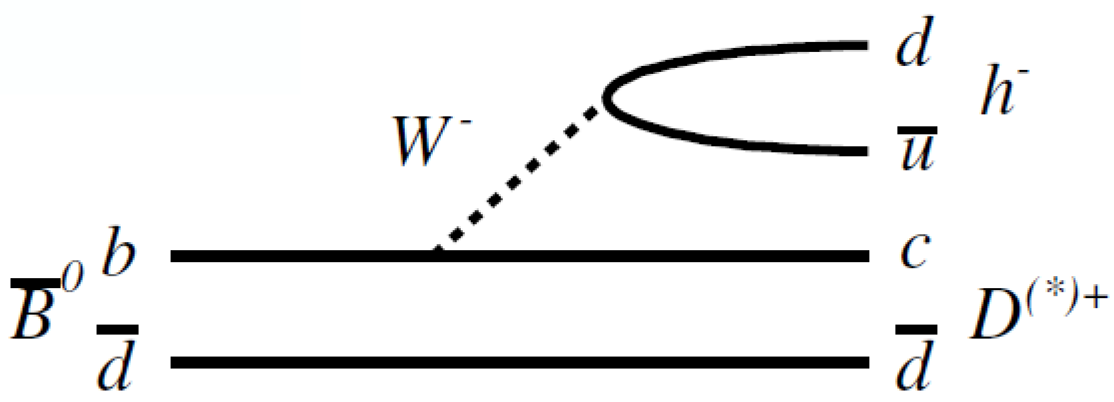
Introduction

Non-leptonic $b \to c$ decays

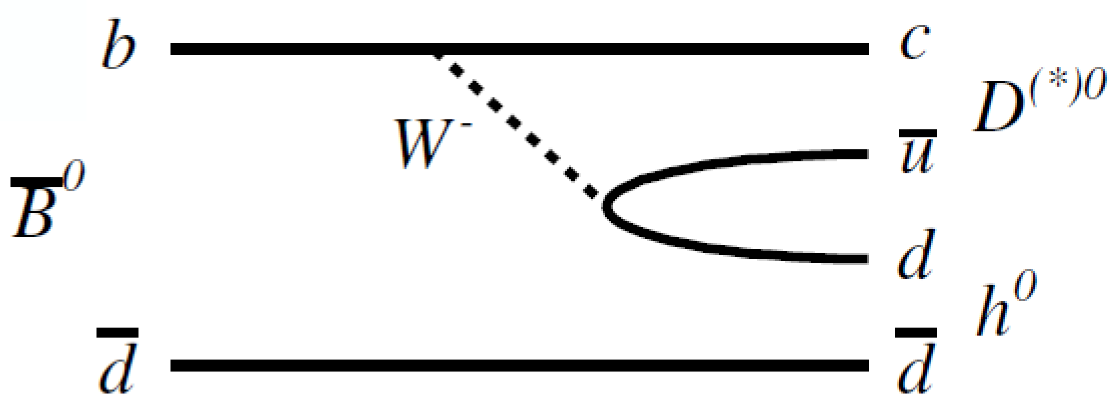
two kinds of non-leptonic B_0 decays mediated by $b \to c$ transitions

color-allowed topology



QCD factorization applicable
no suppression

color-suppressed topology



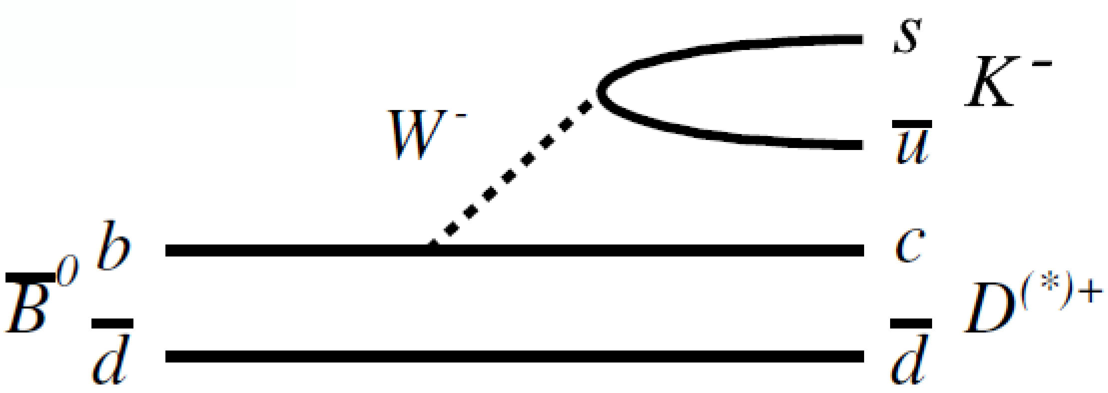
QCD factorization **not** applicable
power-suppressed

The simplest non-leptonic $B_{(s)}$ decays

decays with four different flavors are the simplest
and cleanest non-leptonic $B_{(s)}$

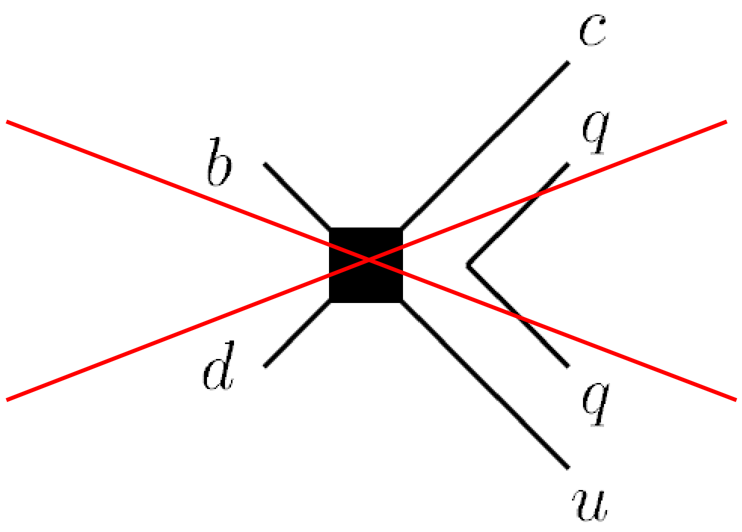
$\Downarrow$

no penguin or annihilation contributions



focus on $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$
to test QCD factorization

[Bordone/NG/Huber/Jung/van Dyk '20]



other color allowed decays discussed
not discussed here

Theoretical framework

Effective Lagrangian

effective Lagrangian for $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$ decays

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} V_{cb}V_{uq}^{*}\left(C_1 O_1^q + C_1 O_1^q\right) + \mathrm{h.c.}$$

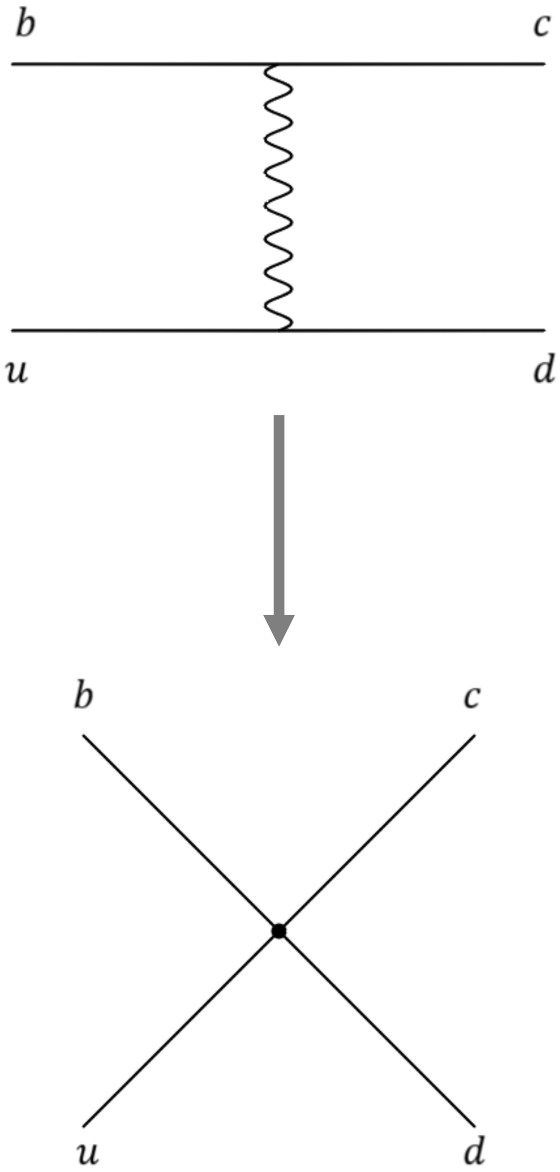
effective operators

$$O_2^{q_2} = (\bar{c}\gamma^\mu P_L T^A b)(\bar{q}\,\gamma_\mu P_L T^A u)$$

$$O_1^q = (\bar{c}\gamma^\mu P_L b)(\bar{q}\,\gamma_\mu P_L u)$$

Wilson coefficients $\boldsymbol{q}$ -flavour universal in the SM

BSM effects may not $\boldsymbol{q}$ -flavour universal



QCD factorization

QCD factorization: systematic method to compute amplitudes in non-leptonic B decays in heavy-quark limit (leading power in $\frac{\Lambda_{\mathrm{QCD}}}{m_b}$) [Beneke/Buchalla(/Neubert/Sachrajda) '99('00)]

$$\mathcal{A}(\bar{B}^0 \to D^+K^-) \propto f_K\, F_0^{B\to D}(M_K^2)\, a_1(D^+K^-) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)$$

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

- Wilson coefficients a_1 computed at NNLO [Huber/Kränkl/Li '16]
- update $B \to D^{(*)}$ and $B_s \to D_s^{(*)}$ form factors [Bordone/NG/Jung/van Dyk '19]
- estimate $\frac{\Lambda_{\mathrm{QCD}}}{m_b}$ corrections **for the first time** [Bordone/NG/Huber/Jung/van Dyk '20]

NNLO calculation of a_1

two-loop corrections to the leading-power hard-scattering kernels [Huber/Kränkl/Li '16]

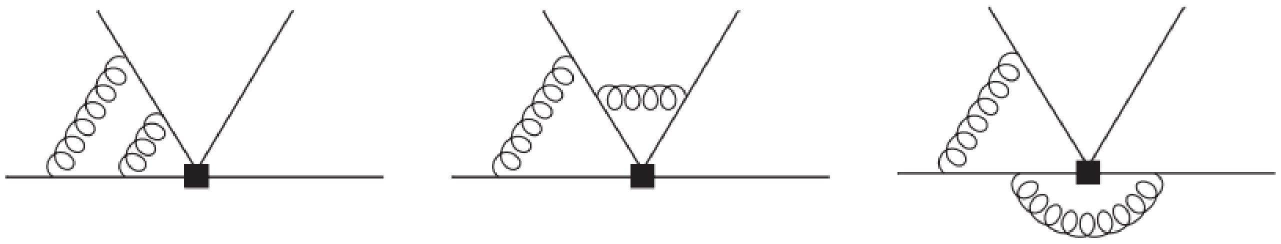
increase the amplitude $\sim 2\%$
($\Longrightarrow$ increase tension with data)

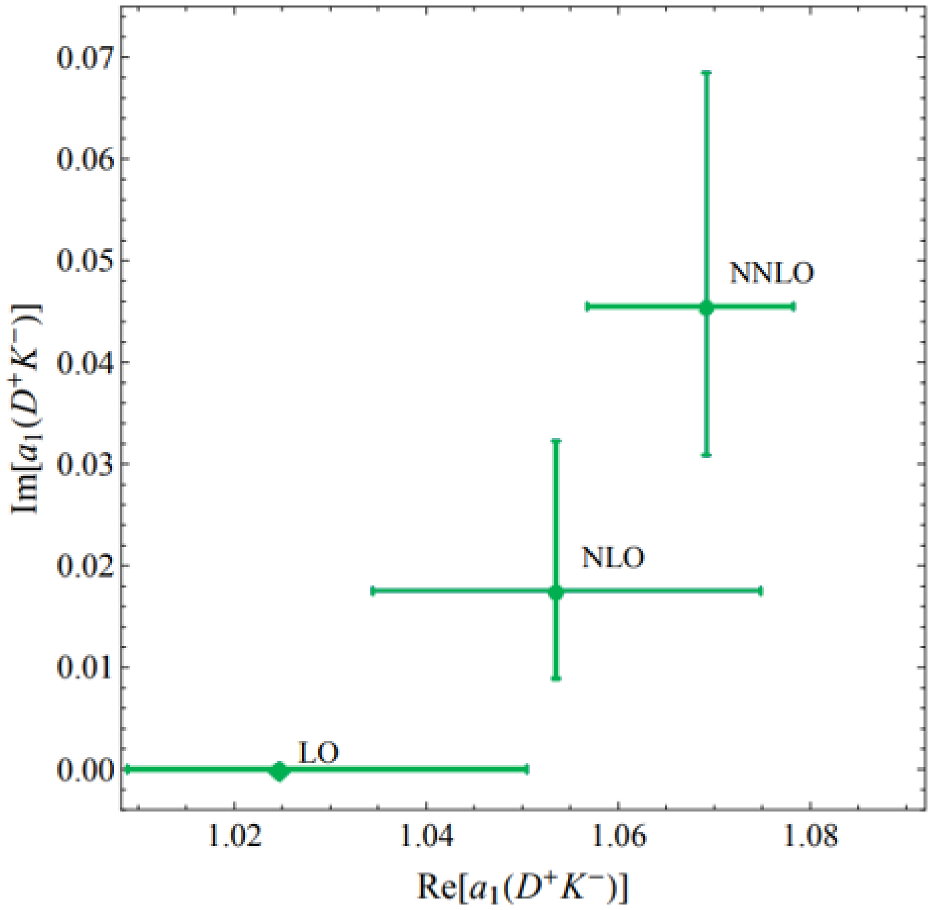
$$|a_1(D_s^+\pi^-)| = 1.073^{+0.012}_{-0.014}$$

$$|a_1(D^+K^-)| = 1.070^{+0.010}_{-0.013}$$

$$|a_1(D_s^{*+}\pi^-)| = 1.071^{+0.013}_{-0.014}$$

$$|a_1(D^{*+}K^-)| = 1.069^{+0.010}_{-0.013}$$





Form factors in HQE

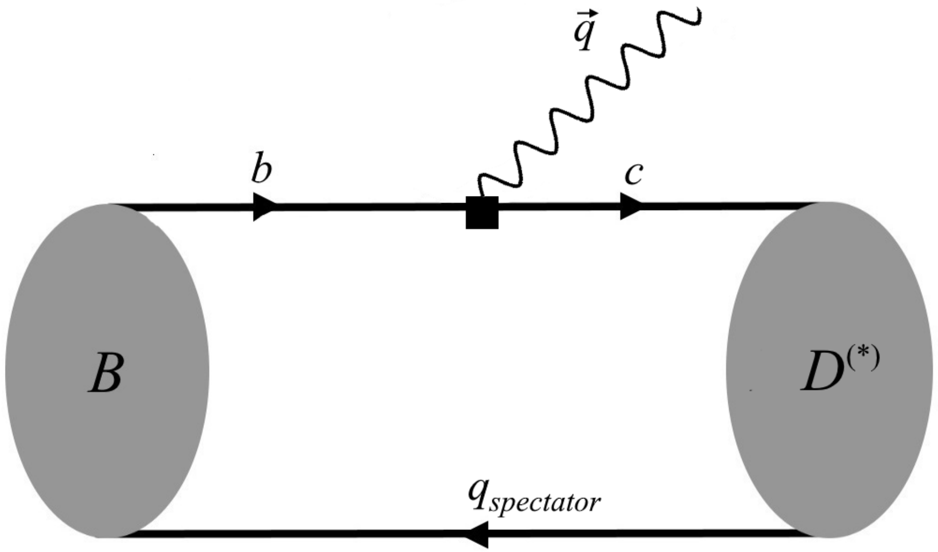
expand $B \to D^{(*)}$ FFs in the limit $m_{b,c} \to \infty$

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

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

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

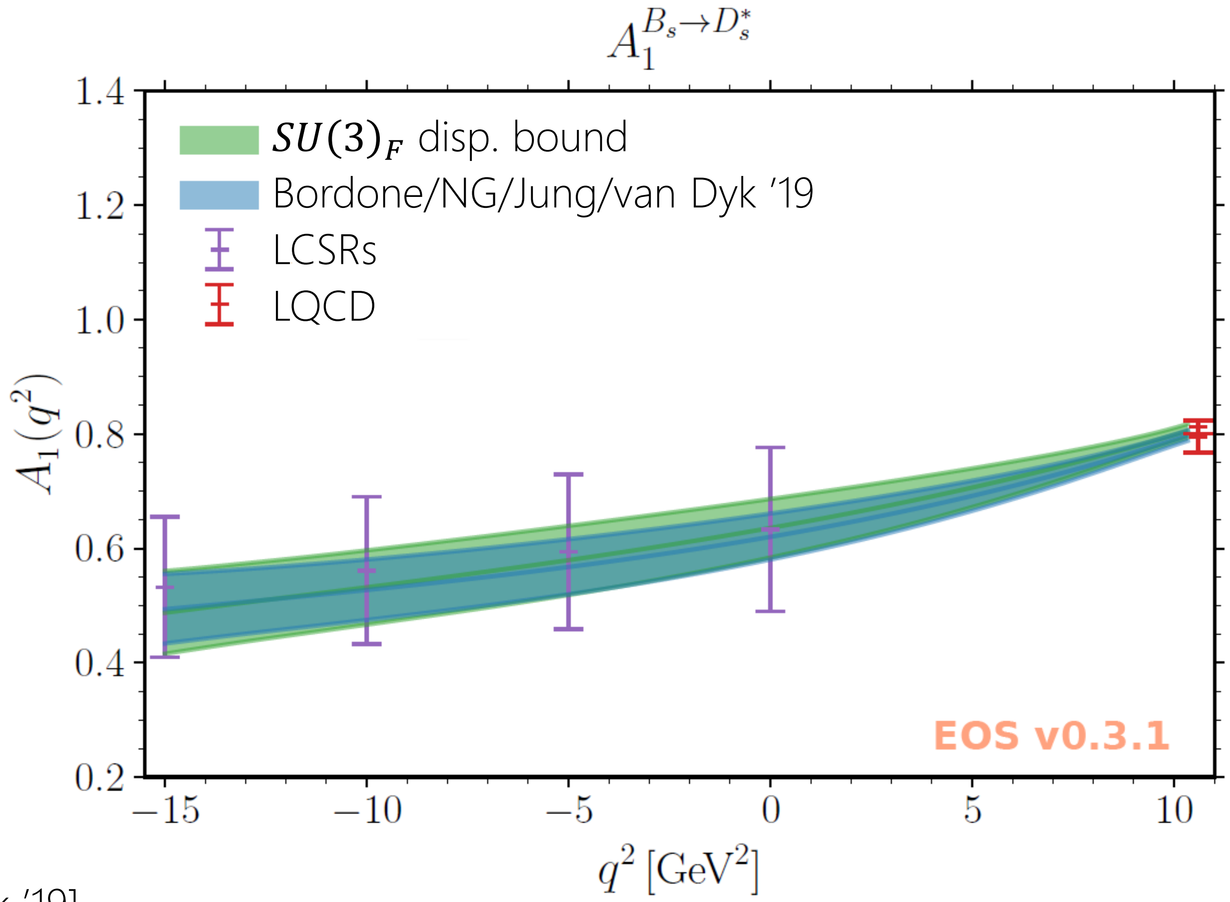
all $B \to D^{(*)}$ and $B_s \to D_s^{(*)}$ FFs parametrized in terms of **14 Isgur-Wise functions**



Form factors predictions

fit Isgur-Wise functions using

- lattice QCD (only A_1 at zero recoil)
- LCSRs for the FFs
- SVZ sum rules for Isgur-Wise functions
- dispersive bounds
- with and w/o exp data



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

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

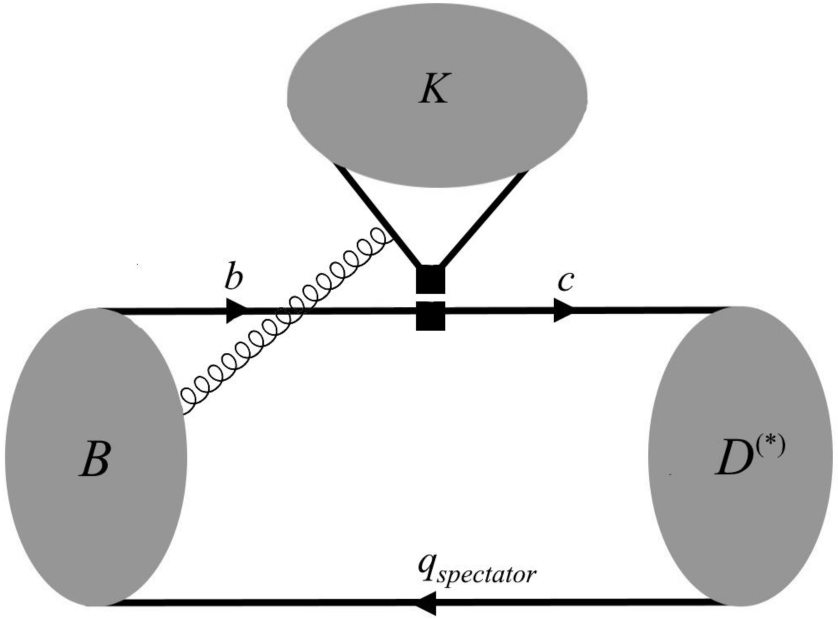
Power corrections

1. no annihilation or penguin topologies no chirally enhanced hard-scattering contributions $\bar{B}_s^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D^{(*)+}K^-$

2. no $\frac{\Lambda_{\mathrm{QCD}}}{m_c}$ corrections since we use QCD form factors instead of soft form factors

3. no hard-collinear gluon between b or c quarks and the light meson at order $\frac{\Lambda_{\mathrm{QCD}}}{m_b}$

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



Light-cone sum rules in a nutshell

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

sum rule

$$\boxed{\left\langle D_q(k)\middle|\mathcal{O}\middle|\bar{B}_q^0(p)\right\rangle = \frac{f_B}{f_D} I(q^2) \otimes \langle 0|\bar{q}(x)\ldots h_v(0)|B(v)\rangle}$$

factorize hard and soft contributions

- compute hard-scattering kernel $I(q^2)$ using **perturbative QCD** at leading order in α_s
- non-local B-to-vacuum matrix elements are a necessary **non-perturbative inputs**

method already applied in Khodjamirian et al 2006, 2008 and 2010 for
local matrix elements in $B \to \pi, \rho, K^{(*)}, D^{(*)}$
nonlocal matrix elements in $B \to K^{(*)}$

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 distribution amplitudes

express B-to-vacuum matrix elements in terms of B-meson light-cone distribution amplitudes (LCDAs)

no two-particle contribution

three-particle contribution:

$$\langle 0|\bar{d}(x)G_{\alpha\beta}(uy)h_v(0)|B(v)\rangle$$
$$= \frac{f_B m_B}{4}\mathrm{Tr}\Big\{\gamma_5 P_+\Big[(v_\alpha\gamma_\beta - v_\beta\gamma_\alpha)(\boldsymbol{\Psi_A}-\boldsymbol{\Psi_V}) - i\sigma_{\alpha\beta}\boldsymbol{\Psi_V} - (y_\alpha v_\beta - y_\beta v_\alpha)\frac{\boldsymbol{X_A}}{v\cdot y} + (y_\alpha\gamma_\beta - y_\beta\gamma_\alpha)\frac{\boldsymbol{W}+\boldsymbol{Y_A}}{v\cdot y}$$
$$- i\epsilon_{\alpha\beta\sigma\rho}y^\sigma v^\rho\gamma_5\frac{\boldsymbol{\widetilde{X}_A}}{v\cdot y} + i\epsilon_{\alpha\beta\sigma\rho}y^\sigma\gamma^\rho\gamma_5\frac{\boldsymbol{\widetilde{Y}_A}}{v\cdot y} - (y_\alpha v_\beta - y_\beta v_\alpha)y_\sigma\gamma^\sigma\frac{\boldsymbol{W}}{(v\cdot y)^2} + (y_\alpha\gamma_\beta - y_\beta\gamma_\alpha)y_\sigma\gamma^\sigma\frac{\boldsymbol{Z}}{(v\cdot y)^2}\Big]\Big\}(\boldsymbol{x},\boldsymbol{uy})$$

new models and higher twist LCDAs triggered our revisiting of the sum rules [Braun/Ji/Manashov '17]

organize LCDAs in a twist expansion (twist = dimension – spin)

higher twists are power of $\Lambda_{\mathrm{had}}/m_B$ suppressed

Light-cone sum rules results

our conservative estimates $L = \{\pi, K\}$

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

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

lower value correspond to our central value
upper value obtained by simply multiplying the central value by a factor of 10

update w.i.p. (see Rusov's talk)

rescattering contribution is negligible (see Iguro's talk)

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

Numerical results
and comparison with data

Theory prediction and comparison with data

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

improved FFs uncertainties

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

updated remaining inputs

source	PDG	QCDF prediction	
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	3.00 ± 0.23	4.42 ± 0.21	$\to 4\sigma$
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.326 ± 0.015	$\to 5\sigma$
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	2.0 ± 0.5	$4.3^{+0.9}_{-0.8}$	$\to 2\sigma$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	0.212 ± 0.015	$0.327^{+0.039}_{-0.034}$	$\to 3\sigma$

discrepancy between measurements and theoretical predictions

New Belle results 1/3

Update of the measurements of $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^-$ [Belle '21]

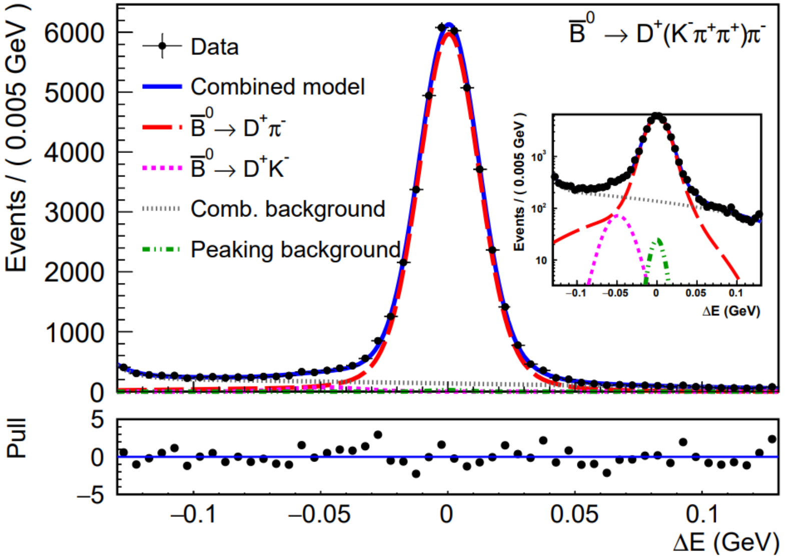
clean from the experimental point of view

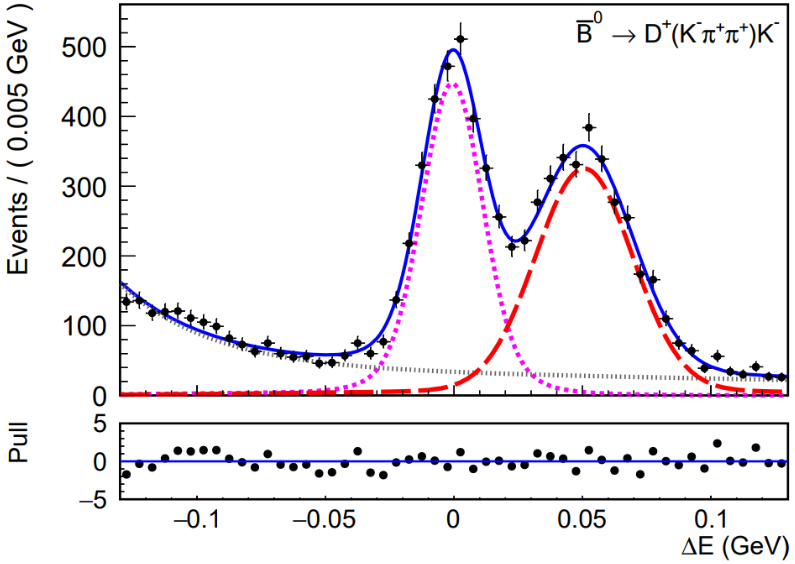
$$\mathcal{B}(\bar{B}^0 \to D^+K^-) = (2.03 \pm 0.05 \pm 0.07 \pm 0.03) \times 10^{-4}$$

increase tension with theory predictions to $\sim 7\sigma$

ratio $\mathcal{B}(\bar{B}^0 \to D^+K^-)/\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$ compatible with theory predictions

corroborate our findings: theory predictions are systematically larger than measurements





New Belle results 2/3

$\bar{B}^0 \to D^{*+}h^-$ measurement

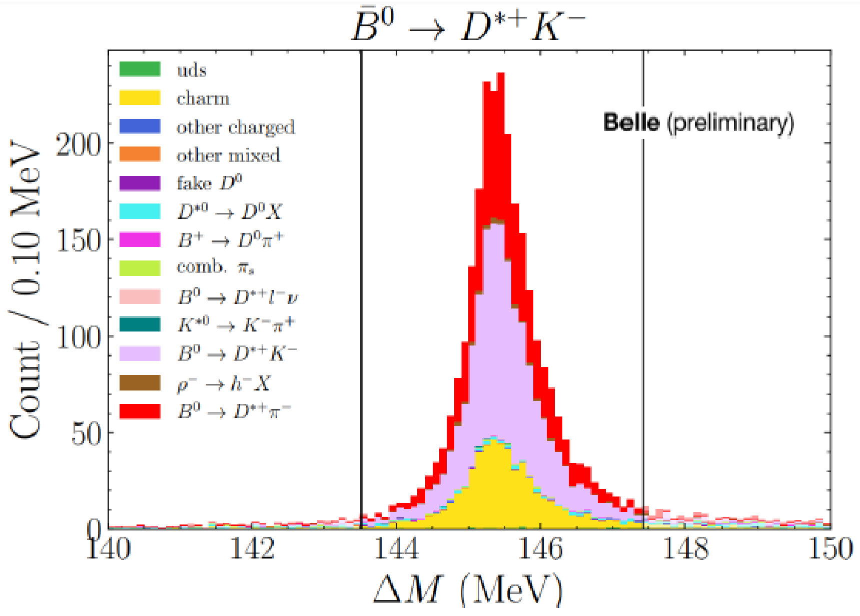
J.F. Krohn et al. (Belle, 2022)

First presentation of results!

- New Belle (711 fb^{-1}) $\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$ and $\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$ measurement, with $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$ or $D^0 \to K^-2\pi^+\pi^-$ (previous 10.4 fb^{-1})

Selection criteria:

- Pion $\mathcal{L}_{K/\pi} < 0.6$ (except slow pions)
- Kaon $\mathcal{L}_{K/\pi} > 0.6$
- D^* candidates have ΔM_{D^*-D} within $\approx$ 2.1MeV/c^2 of mean
- $M_{bc} > 5.27$ GeV/c^2
- $-150 < \Delta E\ (MeV) < 125$

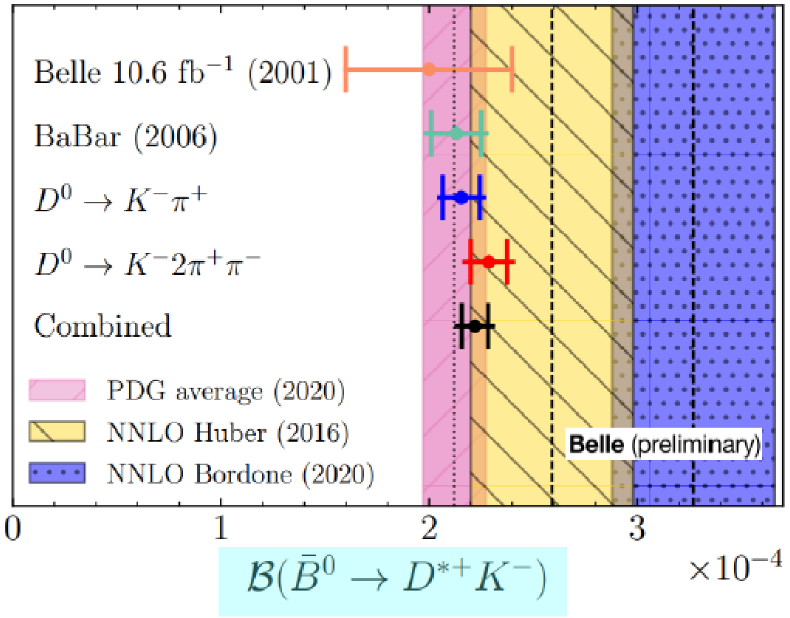


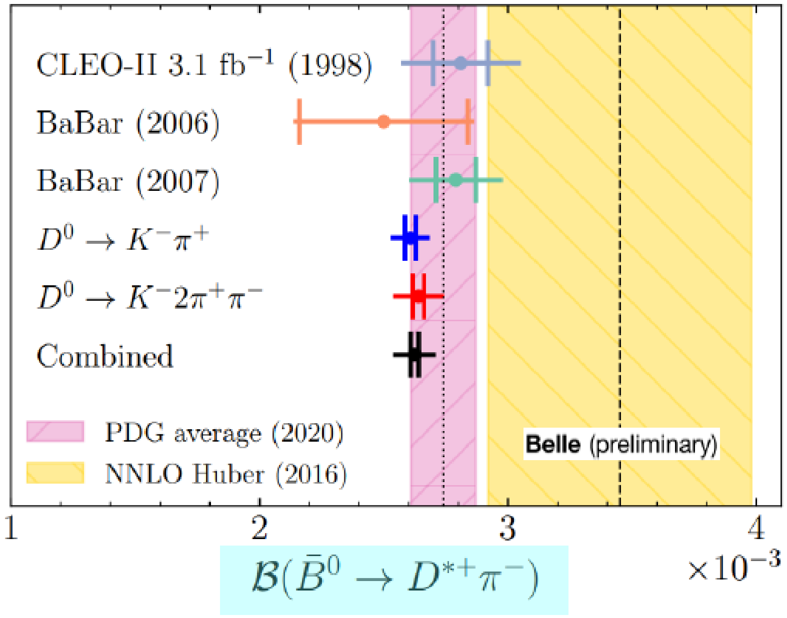
- Signal yields from simultaneous unbinned maximum-likelihood fit of $\Delta E = E_B - E_{beam}$
  - π signal PDF = double Gaussian + Crystal Ball
  - K signal PDF = Gaussian + Crystal Ball
  - Common resolution factor for widths is used for fits to data: $\sigma_i^{data} = \beta\sigma_i^{width}$

New Belle results 3/3

$\bar{B}^0 \to D^{*+}h^-$ measurement

$\sim$**2.6**$\boldsymbol{\sigma}$ tension





$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$		
$D^0 \to K^-\pi^+$	$(2.154 \pm 0.089 \pm 0.078) \times 10^{-4}$	1.1
$D^0 \to K^-2\pi^+\pi^-$	$(2.287 \pm 0.088 \pm 0.092) \times 10^{-4}$	0.7
Combined	$(2.221 \pm 0.063 \pm 0.077) \times 10^{-4}$	0.9

$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	Result	$n\sigma$ meas.$-$theo.
$D^0 \to K^-\pi^+$	$(2.607 \pm 0.023 \pm 0.083) \times 10^{-3}$	1.8
$D^0 \to K^-2\pi^+\pi^-$	$(2.640 \pm 0.022 \pm 0.101) \times 10^{-3}$	1.7
Combined	$(2.623 \pm 0.016 \pm 0.086) \times 10^{-3}$	1.7

$\mathcal{R}_{K/\pi}$		
$D^0 \to K^-\pi^+$	$(8.26 \pm 0.35 \pm 0.16) \times 10^{-2}$	1.8
$D^0 \to K^-2\pi^+\pi^-$	$(8.56 \pm 0.34 \pm 0.16) \times 10^{-2}$	2.5
Combined	$(8.41 \pm 0.24 \pm 0.13) \times 10^{-2}$	2.7

Conclusion

Possible explanations

1. large **nonfactorizable contributions** of $O(15-20\%)$ in the amplitude
   $\longrightarrow$ excluded by our estimate at 4.4σ level

2. **experimental issue** $\longrightarrow$ would imply problems in several (consistent) measurements (CLEO, BaBar, LHCb, Belle)

3. shift in the **inputs** (e.g. V_{ud}, V_{us}, V_{cb}) $\longrightarrow$ would probably violate CKM unitarity

4. **BSM physics** only explanation left $\longrightarrow$ see next slide

5. a combination of the effects discussed above

Is NP a viable option?

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

possibility explored in several works
$\Longrightarrow$ BSM physics viable option
(W' models...)

BSM explanation consistent with flavor observables

[Iguro/Kithahara '21]
[Cai et al. '21]
[Fleischer et al. '20]

however strong constraints from dijet searches

[Bordone/Greljo/Marzocca/Fuentes-Martin '21]

Thank you!