Investigating $\bar{B}_q^0 \to D_q^{(*)+}\{\pi^-, \rho^-, K^{(*)-}\}$ decays in and beyond the Standard Model

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February 7, 2024

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EXCELENCIA MARÍA DE MAEZTU 2020-2023

Studienstiftung des deutschen Volkes

Introduction

What is a *B*-meson?

- bound state of heavy (anti-) *b*-quark and light quark (d, u, s)
- similar to hydrogen atom: heavy proton sources Coulomb field that binds electron

Hydrogen atom

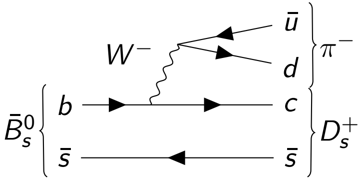
B-meson

Why are B-mesons interesting?

- experimentally accessible
- CP-violation
- constraining CKM matrix elements
- rare decays that are very sensitive to NP
- several tensions of SM prediction and experimental values

Motivation

- consider



- difficult to compute since hadronic and perturbative QCD are hard to disentangle
- "QCD factorization" gives systematic framework to do so

$\bar{B}^0 \to D^{(*)+} K^-$ and $\bar{B}_s^0 \to D_s^{(*)+} \pi^-$ are especially theoretically clean

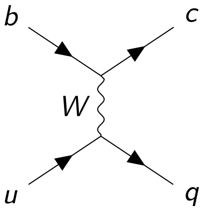
$\lightning$

experimental results

Theoretical Framework

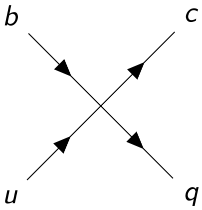
Weak Effective Theory

$\mathcal{H}_{\text{SM}}$



$\longrightarrow$

$\mathcal{H}_{\text{WET}}$



- typical process energy $\ll M_W$
- integrate out W-boson

$$\Downarrow$$

$$\mathcal{H}_{\text{WET}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \left(C_1 \mathcal{Q}_1^{VLL} + C_2 \mathcal{Q}_2^{VLL} \right)$$

$$\mathcal{Q}_1^{VLL} = \left[\bar{c}^\alpha \gamma_\mu (1 - \gamma_5) b^\beta \right] \left[\bar{q}^\beta \gamma^\mu (1 - \gamma_5) u^\alpha \right] , \quad \mathcal{Q}_2^{VLL} = \left[\bar{c}^\alpha \gamma_\mu (1 - \gamma_5) b^\alpha \right] \left[\bar{q}^\beta \gamma^\mu (1 - \gamma_5) u^\beta \right] .$$

Weak Effective Theory

- can be generalized to beyond the Standard Model (BSM) analysis
- effective Hamiltonian for $b \to c\bar{u}q$ decays:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \sum_i \left(C_1^i \mathcal{Q}_1^i + C_2^i \mathcal{Q}_2^i \right) ,$$

with

$$\mathcal{Q}_1^i = \left[\bar{c}^\alpha \Gamma_1^i b^\beta\right] \left[\bar{q}^\beta \Gamma_2^i u^\alpha\right] , \mathcal{Q}_2^i = \left[\bar{c}^\alpha \Gamma_1^i b^\alpha\right] \left[\bar{q}^\beta \Gamma_2^i u^\beta\right] .$$

QCD Factorization

factorization scheme for non-leptonic type I B-decays in the heavy-quark limit:

$$\langle L^- D_q^+ | \mathcal{O}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{B \to D}(m_L^2) \int_0^1 du \, T_{ij}^{\mathrm{I}}(u) \Phi_L(u) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b) \, ,$$

[Beneke/Buchalla/Neubert/Sachrajda '00]

where $L^- \in \{\pi^-, K^-\}$.

$F_j^{B \to D}(m_L^2)$: $\bar{B}_q^0 \to D_q^+$ form factor

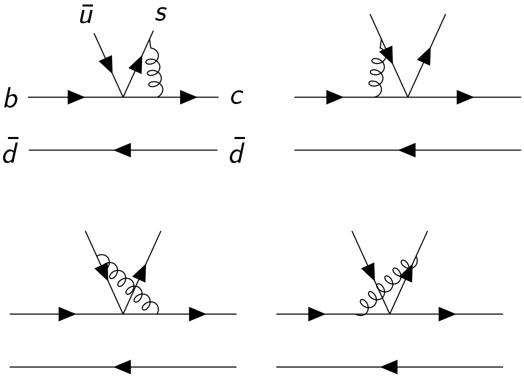
$\Phi_L(u)$: light meson LCDA

$T_{ij}^{\mathrm{I}}(u)$: hard-scattering kernel

$\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$: power-suppressed contributions

Hard-Scattering Kernel

Hard-scattering kernels $T_{ij}^{!}$ at $\mathcal{O}(\alpha_s)^a$ computed from vertex correction diagrams:



$$\langle L^- D_q^+ | \mathcal{O}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{B\to D}(m_L^2) \int_0^1 du\, T_{ij}^{!}(u)\, \Phi_L(u) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$$

Other diagrams

1. power-suppressed
2. included in non-perturbative input
3. not present due to flavor structure

[a] $\mathcal{O}(\alpha_s^2)$ SM result is known [Huber/Kränkl/Li '16]

The Puzzle

The Puzzle in $\bar{B}^0 \to D^+ K^-$ and $\bar{B}_s^0 \to D_s^+ \pi^-$ Decays

QCD factorization prediction within the Standard Model:

$$\mathcal{B}\left(\bar{B}^0 \to D^+ K^-\right) = (0.326 \pm 0.015) \cdot 10^{-3}$$
$$\mathcal{B}\left(\bar{B}_s^0 \to D_s^+ \pi^-\right) = (4.42 \pm 0.21) \cdot 10^{-3}$$

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

experimental values:

$$\mathcal{B}\left(\bar{B}^0 \to D^+ K^-\right) = (0.186 \pm 0.020) \cdot 10^{-3}$$
$$\mathcal{B}\left(\bar{B}_s^0 \to D_s^+ \pi^-\right) = (3.00 \pm 0.23) \cdot 10^{-3}$$

PDG/LHCb/Belle/BaBar/CLEO/ARGUS

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strong tension in $\bar{B}_s^0 \to D_s^+ \pi^-$ and $\bar{B}^0 \to D^+ K^-$

Possible Explanations for the Puzzle

$$\langle L^- D_q^+ | \mathcal{O}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{B\to D}(m_L^2) \int_0^1 du\, T_{ij}^{\rm I}(u)\, \Phi_L(u) + \mathcal{O}(\Lambda_{\rm QCD}/m_b)$$

1. Large **non-factorizable contributions** : unlikely
   - $\mathcal{O}(15-20\%)$ at amplitude level necessary
   - disfavored by LCSR estimate [Bordone/Gubernari/Huber/Jung/van Dyk '20]
2. **Experimental issue**: unlikely
   - only charged final state particles
   - would imply problems in several consistent measurements
3. **Shift in parametric inputs**: unlikely
   - V_{cb}, V_{us}, V_{ud} well known
   - shift would violate CKM unitarity
4. **New physics**: only possibility left, but is it viable?

New Physics as Explanation for the Puzzle

- BSM interpretation studied in literature [Cai et al. '21]
- one-loop hard-scattering kernels for the full basis of BSM operators
- fit to $R^{(*)}_{(s)L} = \frac{\Gamma(\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} L^-)}{d\Gamma(\bar{B}^0_{(s)} \to D^{+(*)}_{(s)} \ell^- \bar{\nu}_\ell)/dq^2|_{q^2=m_L^2}}$ with one and two allowed BSM contributions

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Only some vector and scalar Dirac structures can explain data

Possible Problems with [Cai et al. '21]

$$\langle L^- D_q^+ | \mathcal{O}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{B\to D}(m_L^2) \int_0^1 du\, T_{ij}^{\text{I}}(u)\, \Phi_L(u) + \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$$

1. renormalization scheme used for the calculation not explicitly stated
2. power suppressed contributions from three-particle states not discussed
3. for some operators no published results for the $m_c \to 0$ limit

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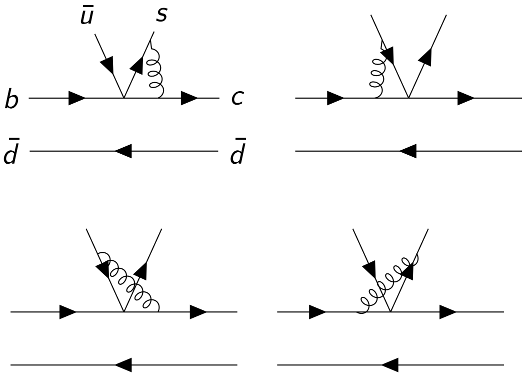
my goal:

- recalculate one-loop hard-scattering kernels
- calculate power suppressed contributions

Results

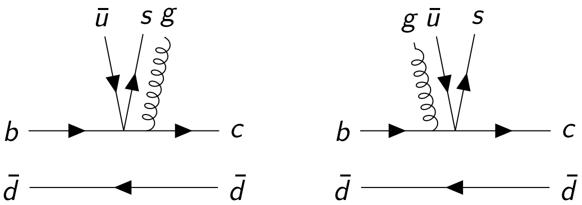
Hard-Scattering Kernels



- recalculated all twenty hard-scattering kernels and found agreement with literature [Cai et al. '21]
- renormalization scheme stated explicitly, consistent with other existing calculations
- checked $m_c \to 0$ limit [Beneke, Buchalla, Neubert, Sachrajda '01], [Beneke, Neubert '03]

Three-Particle States

contribution from three-particle light meson state :



non-zero contributions only for vector and tensor operators:

- vector: $m_c \to 0$ limit differs by $1/N$ compared to literature [Beneke, Buchalla, Neubert, Sachrajda '00]
- tensor: contributions are highly suppressed

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1. three-particle states are under control in and beyond the Standard Model
2. decays even cleaner than assumed

Pheno-Analysis

- pheno-analysis is being performed with EOS
- tree-level and one-loop results implemented in EOS
- three-particle contributions are work in progress
- fit: plan to fit all 20 WC simultaneously with ~ 40 parameters related to form-factors and ~ 10 parameters related to the experimental branching ratios

[van Dyk et al. '21]

Summary and Outlook

- B-mesons are interesting laboratories for new physics
- some tensions with SM predictions persist
- SM predictions for $\bar{B}_{(s)} \to D^+_{(s)}\{\pi^-, K^-\}$ BRs are way off
  $\to$ possible new physics?
- calculated one-loop hard-scattering kernels for all twenty operators and found agreement with literature
- calculated contributions from three parton light meson states
  $\to$ found $1/N$ discrepancy in SM result
  $\to$ three particle BSM contributions highly suppressed
- perform more exhaustive pheno-analysis

Non-Leading Fock State - Twist 3 and Twist 4 LCDAs

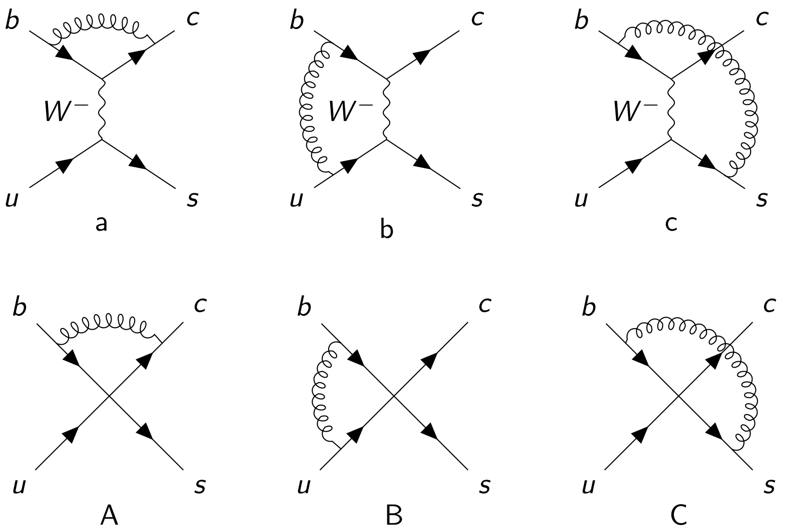
Twist 3:

$$\langle L^-(q)|\,\bar{q}(0)\sigma_{\mu\nu}\gamma_5 g_s G_{\alpha\beta}(vx)u(0)\,|0\rangle = if_{3L}[(q_\alpha q_\mu g_{\beta\nu} - q_\beta q_\mu g_{\nu\alpha}) - (\mu \leftrightarrow \nu)] \int \mathcal{D}u e^{ivu_3 q\cdot x}\phi_{3L}(u_i)$$

Twist 4:

$$\begin{aligned}\langle L^-(q)|\,\bar{q}(0)\gamma_\mu\gamma_5 g_s G_{\alpha\beta}(vx)u(0)\,|0\rangle =& f_L \int \mathcal{D}u\; e^{ivu_3 q\cdot x}\Big\{ [q_\beta g_{\alpha\mu} - q_\alpha g_{\beta\mu}]\,\phi_\perp(u_i) \\ &+ \left[\frac{q_\mu q_\alpha x_\beta}{q\cdot x} - \frac{q_\mu q_\beta x_\alpha}{q\cdot x}\right](\phi_\parallel(u_i) + \phi_\perp(u_i))\Big\} \\ \langle L^-(q)|\,\bar{q}(0)\gamma_\mu g_s \tilde{G}_{\alpha\beta}(vx)u(0)\,|0\rangle =& if_L \int \mathcal{D}u\; e^{ivu_3 q\cdot x}\Big\{ [q_\beta g_{\alpha\mu} - q_\alpha g_{\beta\mu}]\,\tilde{\phi}_\perp(u_i) \\ &+ \left[\frac{q_\mu q_\alpha x_\beta}{q\cdot x} - \frac{q_\mu q_\beta x_\alpha}{q\cdot x}\right]\left(\tilde{\phi}_\parallel(u_i) + \tilde{\phi}_\perp(u_i)\right)\Big\}\end{aligned}$$

Matching and Renormalization Group Running



Hard-Scattering Kernels - Calculation

$$\langle D^+_{(s)} L^- | \mathcal{Q}^i_1 | \bar{B}^0_{(s)} \rangle_{\text{1-gluon}}$$
$$= -ig_s^2 \frac{C_F}{N} \int \frac{d^4k}{(2\pi)^4} \langle D^+_{(s)} | \bar{c} A^i_1(k) b | \bar{B}^0_{(s)} \rangle \frac{1}{k^2} \int_0^1 du \, \mathrm{Tr} \left[M^L(u) A^i_2(uq, \bar{u}q, k) \right] ,$$

with

$$A^i_1(k) = \gamma^\beta \frac{\not{p}_c - \not{k} + m_c}{2p_c \cdot k - k^2} \Gamma^i_1 - \Gamma^i_1 \frac{\not{p}_b + \not{k} + m_b}{2p_b \cdot k + k^2} \gamma^\beta ,$$

$$A^i_2(l_q, l_{\bar{q}}, k) = \Gamma^i_2 \frac{\not{l}_{\bar{q}} + \not{k}}{2l_{\bar{q}} \cdot k + k^2} \gamma_\beta - \gamma_\beta \frac{\not{l}_q + \not{k}}{2l_q \cdot k + k^2} \Gamma^i_2 ,$$

$$M^L_{\alpha\delta} = \frac{if_L}{4} \left\{ \not{q} \gamma_5 \phi_L(u) - \mu_P \gamma_5 \left(\phi_p(u) - i\sigma_{\mu\nu} n^\mu_+ n^\nu_- \frac{\phi'_\sigma(u)}{12} + i\sigma_{\mu\nu} q^\mu \frac{\phi_\sigma(u)}{6} \frac{\partial}{\partial l_{q\perp\nu}} \right) \right\}_{\delta\alpha} .$$

ϕ_L : twist-2, vector operators

ϕ_p , ϕ_σ : twist-3, scalar/tensor operators

Likelihood

measurement	value	source	reference(s)
$\mathcal{B}(B_s^0 \to D_s^- \pi^+)$	$(3.6 \pm 0.5 \pm 0.5)\, 10^{-3}$	Belle	[15, 21]
$\frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \to D_s^-(\to \phi(\to K^+K^-)\pi^-)\pi^+)}{\mathcal{B}(B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+)}$	$(6.7 \pm 0.5)\%$	CDF	[41]*
$\frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \to D_s^-(\to K^+K^-\pi^-)\pi^+)}{\mathcal{B}(B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+)}$	0.174 ± 0.007	LHCb	[42]
$\frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \to D_s^-(\to K^+K^-\pi^-)\pi^+)}{\mathcal{B}(B^0 \to D^-(\to K^+\pi^-\pi^-)K^+)}$	2.08 ± 0.08	LHCb	[25]†
$\frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$	$(8.22 \pm 0.28)\%$	LHCb	[25]†
$\frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$	$(6.8 \pm 1.7)\%$	Belle	[43]
$f_{00}\mathcal{B}(B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+)$	$(1.21 \pm 0.05)\, 10^{-4}$	BaBar/CLEO	[24, 44]
$\mathcal{B}(B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+)$	$(2.88 \pm 0.29)\, 10^{-4}$	BaBar	[45]§
$\frac{\mathcal{B}(B_s^0 \to D_s^{*-} \pi^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}$	0.66 ± 0.16	Belle	[46]
$\frac{\mathcal{B}(B^0 \to D^{*-} K^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+)}$	$(7.75 \pm 0.30)\%$	LHCb/BaBar/Belle	[43, 47, 48]
$f_{00}\mathcal{B}(B^0 \to D^{*-}\pi^+)$	$(2.72 \pm 0.14)\, 10^{-3}$	BaBar/CLEO	[24, 49]
$\frac{\mathcal{B}(B^0 \to D^{*-} \pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$	0.99 ± 0.14	BaBar	[45]
$\mathcal{B}(D_s^- \to \phi(\to K^+K^-)\pi^-)$	$(2.27 \pm 0.08)\%$	PDG average	[15]
$\mathcal{B}(D_s^- \to K^+K^-\pi^-)$	$(5.45 \pm 0.17)\%$	PDG average	[15]
$\mathcal{B}(D^- \to K^+\pi^-\pi^-)$	$(9.38 \pm 0.16)\%$	PDG average	[15]
$\mathcal{B}(D_s^- \to K^+K^-\pi^-)(f_s/f_d)^{7\text{TeV}}_{\text{LHCb,sl}}$	0.0144 ± 0.0010	LHCb	[22, 23]
$\mathcal{B}(D_s^- \to K^+K^-\pi^-)(f_s/f_d)^{13\text{TeV}}_{\text{LHCb,sl}}$	0.0133 ± 0.0005	LHCb	[50]
$(f_s/f_d)_{\text{Tev}}$	0.334 ± 0.040	HFLAV average	[29]
f_{00}	0.488 ± 0.010	pheno comb. of BaBar/Belle	[40, 51, 52]

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

Fit Results

source	PDG	our fits (w/o QCDF)		our fit (w/ QCDF, no f_s/f_d)		QCDF prediction
scenario	—	no f_s/f_d	$(f_s/f_d)^{7\,\text{TeV}}_{\text{LHCb,sl}}$	ratios only	~~$SU(3)$~~	—
χ^2/dof	—	2.5/4	3.1/5	4.6/6	3.7/4	—
$\mathcal{B}(\bar{B}^0_s \to D^+_s \pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21
$\mathcal{B}(B^0 \to D^+ K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.227 ± 0.012	0.226 ± 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	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	—
$\mathcal{B}(\bar{B}^0_s \to D^{*+}_s \pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(B^0 \to D^{*+} K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	—
$\mathcal{R}^P_{s/d}$	16.1 ± 2.1	16.2 ± 3.3	14.0 ± 1.1	13.6 ± 0.6	$14.2^{+0.6}_{-1.1}$ *	$13.5^{+0.6}_{-0.5}$
$\mathcal{R}^V_{s/d}$	9.4 ± 2.5	11.4 ± 3.6	9.6 ± 2.5	$11.4^{+1.7}_{-1.6}$	$11.4^{+1.7}_{-1.5}$ *	$13.1^{+2.3}_{-2.0}$
$\mathcal{R}^{V/P}_s$	0.66 ± 0.16	0.66 ± 0.16	0.66 ± 0.16	$0.81^{+0.12}_{-0.11}$	$0.76^{+0.11}_{-0.10}$	$0.97^{+0.20}_{-0.17}$
$\mathcal{R}^{V/P}_d$	1.14 ± 0.15	0.97 ± 0.08	0.97 ± 0.08	0.97 ± 0.06	0.95 ± 0.07	1.01 ± 0.11
$(f_s/f_d)^{7\,\text{TeV}}_{\text{LHCb}}$	—	$0.223^{+0.056}_{-0.038}$ *	0.260 ± 0.019	$0.261^{+0.018}_{-0.016}$	$0.252^{+0.023}_{-0.015}$ *	—
$(f_s/f_d)_{\text{Tev}}$	—	$0.208^{+0.056}_{-0.038}$ *	0.243 ± 0.028	$0.244^{+0.026}_{-0.023}$	$0.236^{+0.026}_{-0.022}$ *	—
Δ_P	—	—	—	$-0.164^{+0.030}_{-0.028}$	-0.167 ± 0.029	—
Δ_V	—	—	—	$-0.20^{+0.06}_{-0.05}$	$-0.20^{+0.06}_{-0.05}$	—

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