Exclusive b-quark decays

– Projects C2a and C2b –

CRC Annual Meeting
March 2024

Thorsten Feldmann

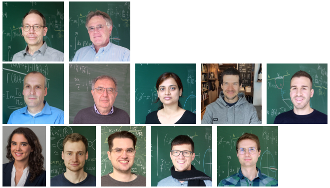
Universität Siegen
TP1 Theoretical Particle Physics
CPPS Center for Particle Physics Siegen

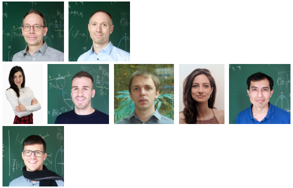
CRC TRR 257
Particle Physics Phenomenology after the Higgs Discovery

Work Areas for the second funding period

C2a: Hadronic matrix elements and exclusive semileptonic decays

- WA1: Factorization and light-cone distributions
- WA2: QCD sum rules and related methods
- WA3: New channels and multi-hadron final states
- WA4: Inclusive rates and the sum over exclusive channels,
  Semi-inclusive decays





C2b: Exclusive non-leptonic and rare b-quark decays

- WA1: Higher-order QCD corrections
- WA2: Phenomenology of non-leptonic decays
- WA3: Phenomenology of rare decays,
  BSM flavour structures

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new members since fall 2023: Anshika Bansal (C2a), Jack Jenkins (C2b)

Factorization and light-cone distributions

1. T. Feldmann, P. Lüghausen and N. Seitz,
"Strange-quark mass effects in the B_s meson's light-cone distribution amplitude,"
JHEP **08** (2023), 075 [arXiv:2306.14686 [hep-ph]].

2. T. Feldmann and N. Gubernari,
"Non-factorisable Contributions of Strong-Penguin Operators in $\Lambda_b \to \Lambda \ell^+ \ell^-$ Decays," $\leftrightarrow$ C2b
[arXiv:2312.14146 [hep-ph]] (to appear in JHEP).

3. P. Böer, G. Bell, T. Feldmann, D. Horstmann and V. Shtabovenko,
"Soft-overlap contribution to $B_c \to \eta_c$ form factors: diagrammatic resummation of double logarithms,"
PoS **RADCOR2023** (2024), 086 [arXiv:2309.08410 [hep-ph]] $\leftrightarrow$ B1e
(detailed write-up in preparation)

Strange-quark mass effects in the B_s meson light-cone distribution amplitude

T. Feldmann, P. Lüghausen and N. Seitz, JHEP **08** (2023), 075

short-distance OPE of light-ray operator in HQET: $(n^2 = 0)$

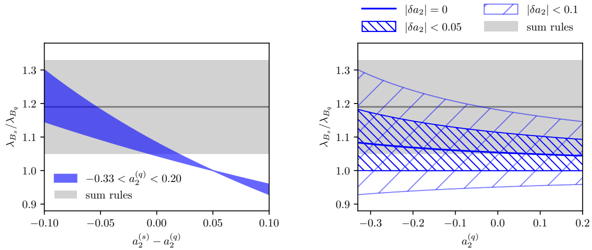
$$\bar q(\tau n)[\tau n, 0]\not{n}\gamma_5\, h_v(0)$$
$$= c_1^{(3)}(\tau)\, \bar q\, \not{n}\gamma_5\, h_v + c_1^{(4)}(\tau)\, \bar q\, (in\cdot \overleftarrow{D})\, \not{n}\gamma_5\, h_v$$
$$+\, c_2^{(4)}(\tau)\, \bar q\, (iv\cdot \overleftarrow{D})\, \not{n}\gamma_5\, h_v + c_3^{(4)}(\tau)\, m_s\, \bar q\, \not{v}\not{n}\gamma_5\, h_v$$
$$+ \dots$$

→ short-distance behaviour of LCDA $\tilde\phi^+_{B_s}(\tau)$ in terms of HQET parameters ($\bar\Lambda_s = m_{B_s} - m_b$ etc.)

→ 1-loop calculation of Wilson coefficient $c_3^{(4)}(\tau)$

→ extrapolation to large $\tau \sim 1/\Lambda_{\rm had}$ by means of generic parametrization

[TF, P. Lüghausen and D. van Dyk, JHEP **10** (2022), 162]



estimates for first inverse moments $\lambda_B^{-1} = \int \frac{d\omega}{\omega}\, \phi_B^+(\omega)$

- our results for λ_{B_q} and λ_{B_s} compare well with QCD sum rule estimates ✓

  [A. Khodjamirian, R. Mandal and T. Mannel, JHEP **10** (2020), 043]

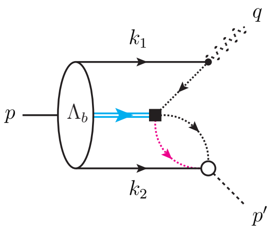
- OPE and QCD-SR constraints can be used consistently in global fits ✓

  [TF, Lüghausen, van Dyk, work in progress]

Non-factorisable contributions of strong-penguin operators in $\Lambda_b \to \Lambda \ell^+ \ell^-$ (I)

T. Feldmann and N. Gubernari, arXiv:2312.14146 (to appear in JHEP)

- sum-rule approach to $\Lambda_b \to \Lambda\gamma^*$ with interpolating current for Λ
- leads to "annihilation-like" decay topologies with 4-quark operators: $\blacksquare = (\bar{s}\ldots b)(\bar{q}\ldots q)$



- light-quark momenta (k_1, k_2) couple to external momenta (q, p') in *different* light-cone directions
- requires specific "soft Λ_b functions", where light-quark fields are separated along *different* light rays

$$\langle 0| d(\tau_2 \bar{n})\, u(\tau_1 n)\, h_v^{(b)}(0) |\Lambda_b(p)\rangle$$

$\to$ need to generalize and model 3-quark LCDAs for Λ_b ✓

$\to$ expect similar new features as for soft B-meson functions, with additional photons or gluons in opposite light-cone direction

e.g. [M. Beneke, P. Böer, J. N. Toelstede and K. K. Vos, JHEP **08** (2022), 020],

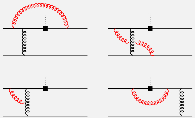
[Y. K. Huang, Y. Ji, Y. L. Shen, C. Wang, Y. M. Wang and X. C. Zhao, arXiv:2312.15439 [hep-ph]

to be worked out ...

$B_c \to \eta_c$ form factors: diagrammatic resummation of double logs

P. Böer, G. Bell, T. Feldmann, D. Horstmann and V. Shtabovenko, PoS **RADCOR2023** (2024), 086

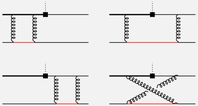
Sudakov logs from (on-shell) soft gluons:



standard exponentiation:

$$\exp\left[-\frac{\alpha_s C_F}{2\pi}\ln\frac{p_-}{k_-}\ln\frac{\ell_+}{k_+}\right]$$

endpoint logs from (on-shell) soft quarks:



iterative pattern
of double convolutions

similar to $e\mu$ backward scattering

[Bell, Böer, Feldmann, JHEP **09** (2022), 183]

tower of large double logs $\left(\alpha_s \ln^2 \frac{p_-}{m}\right)^n$ encoded in coupled integral equations for "soft form factors"

$$f(\ell_+,\ell_-) = 1 + \frac{\alpha_s C_F}{2\pi}\int_{\ell_-}^{p_-}\frac{dk_-}{k_-}\int_{m^2/k_-}^{\ell_+}\frac{dk_+}{k_+}\,e^{-S(k_+,k_-)}\left(f(k_+,k_-) - \frac{C_{FA}}{2C_F}f_m(k_+,k_-) + \frac{C_A}{4C_F}\right)$$

$$f_m(\ell_+,\ell_-) = 1 + \frac{\alpha_s C_F}{2\pi}\int_{\ell_-}^{p_-}\frac{dk_-}{k_-}\int_{m^2/k_-}^{\ell_+}\frac{dk_+}{k_+}\,e^{-S(k_+,k_-)}\,f_m(k_+,k_-)$$

$\to$ iterative solution ✓ asymptotic behaviour ✓ $\to$ see also Guido Bell's presentation

1. N. Gubernari, A. Khodjamirian, R. Mandal and T. Mannel, "$B \to D_0^*$ and $B_s \to D_{s0}^*$ form factors from QCD light-cone sum rules," JHEP **12**, 015 (2023)

2. S. Descotes-Genon, A. Khodjamirian, J. Virto and K. K. Vos, "Light-Cone Sum Rules for S-wave $B \to K\pi$ Form Factors," JHEP **06** (2023), 034. [arXiv:2304.02973 [hep-ph]].

$B \to D_0^*$ and $B_s \to D_{s0}^*$ form factors from QCD light-cone sum rules

N. Gubernari, A. Khodjamirian, R. Mandal and T. Mannel, JHEP **12** (2023), 015

- estimates of $b \to c\ell\nu$ decays into excited D-mesons are important to understand the gap between inclusive $b \to c\ell\nu$ and sum over exclusive channels $\to$ WA4
- previous analysis for axial-vector mesons ($J^P = 1^+$) [Gubernari, Khodjamirian, Mandal, Mannel, JHEP **05**, 029 (2022)]
- here: for scalar D-mesons ($J^P = 0^+$)

calculational setup:

- use LCSRs with B-meson LCDAs (i.e. large recoil, finite charm mass)
- include 2- and 3-particle LCDAs (incl. twist-4)
- decay constants from 2-point sum rules
- z-expansion to extrapolate to small recoil

two different scenarios for scalar D-mesons:

(1) one single broad resonance (PDG)

(2) two individual resonances (from $B \to D\pi\pi$) $\to$ WA3

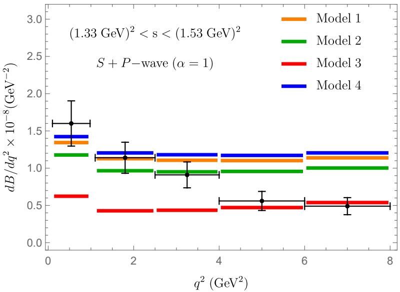
Scenario	Meson	Mass [MeV]	Width [MeV]
1	$D_0^* \equiv D_0^*(2300)$	2343 ± 10	229 ± 16
	$D_{s0}^* \equiv D_{s0}^*(2317)$	2317.8 ± 0.5	< 3.8
2	$D_0^* \equiv D_0^*(2105)$	2105^{-8}_{+6}	204^{+20}_{-22}
	$D_0^{*\prime} \equiv D_0^*(2451)$	2451^{-26}_{+35}	268^{+14}_{-16}
	$D_{s0}^* \equiv D_{s0}(2317)$	2317.8 ± 0.5	< 3.8
	$D_{s0}^{*\prime} \equiv D_{s0}^*(2660)$	~ 2660	—

Scenario 1	Scenario 2
$\mathcal{B}(\bar{B}^0 \to D_0^* \ell\bar{\nu}) = (3.6^{+5.1}_{-3.0}) \cdot 10^{-3}$	$\mathcal{B}(\bar{B}^0 \to D_0^* \ell\bar{\nu}) = (1.6^{+3.2}_{-1.4}) \cdot 10^{-3}$
$\mathcal{B}(\bar{B}^0 \to D_0^* \tau\bar{\nu}) = (3.9^{+5.1}_{-3.1}) \cdot 10^{-4}$	$\mathcal{B}(\bar{B}^0 \to D_0^* \tau\bar{\nu}) = (2.4^{+4.7}_{-2.1}) \cdot 10^{-4}$
$\mathcal{B}(\bar{B}_s \to D_{s0}^* \ell\bar{\nu}) = (1.9^{+3.8}_{-1.7}) \cdot 10^{-3}$	$\mathcal{B}(\bar{B}^0 \to D_0^{*\prime} \ell\bar{\nu}) = (2.3^{+1.4}_{-1.8}) \cdot 10^{-3}$
$\mathcal{B}(\bar{B}_s \to D_{s0}^* \tau\bar{\nu}) = (2.6^{+4.9}_{-2.2}) \cdot 10^{-4}$	$\mathcal{B}(\bar{B}^0 \to D_0^{*\prime} \tau\bar{\nu}) = (1.9^{+1.1}_{-1.4}) \cdot 10^{-4}$

Light-Cone Sum Rules for S-wave $B \to K\pi$ Form Factors

S. Descotes-Genon, A. Khodjamirian, J. Virto and K. K. Vos, JHEP **06** (2023), 034

- estimate of (non-resonant) $B \to K\pi\ell^+\ell^-$ important for accurate analysis of $B \to K^*\ell^+\ell^-$ $\to$ C2b
- earlier studies focused on P-wave contributions [Descotes-Genon, Khodjamirian, Virto, JHEP 12, 083 (2019)]
- standard LCSR setup with B-meson LCDAs (incl. twist-4)
- S-wave $K\pi$ spectrum from coupled-channel analysis, [Von Detten, Noel, Hanhart, Hoferichter, Kubis, Eur. Phys. J. C 81, no.5, 420 (2021)]
  $\to$ 4 different models, fitted to $K\pi$ scattering data



Comparison with LHCb data around $K^*(1410)$, $K^*(1430)$

- significant S-wave contribution (incl. interference with P-wave)
- correct order of magnitude
- unsatisfactory q^2 dependence

$\to$ refine the model for the $K\pi$ spectrum

$\to$ implications for other multi-hadron channels $\to$ WA3

($B \to \pi\pi\ell\bar{\nu}$, $B \to \pi\pi\ell^+\ell^-$, $B \to K\pi\nu\bar{\nu}$, $B \to K\pi\pi$, $B \to K\pi a$, $B \to K\pi\gamma'$, ...)

New channels and multi-hadron final states

1. A. Boushmelev and M. Wald,
"Higher twist corrections to B-meson decays into a proton and dark antibaryon ...,"
arXiv:2311.13482 [hep-ph]

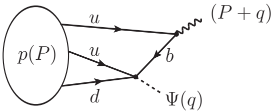
- Mannel, Tetlalmatzi-Xolocotzi, Descotes-Genon, LHCb (Paris, LPTHE)
improved description of non-resonant region for $B^0 \to K^+ K^- K_S$
including $c\bar{c}$ threshold effects
work in progress

builds on [Mannel, Olschewsky, Vos, JHEP **06**, 073 (2020)])

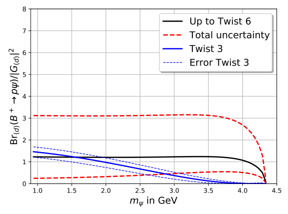
B-meson decays into a proton and dark antibaryon from LCSRs

[A. Boushmelev and M. Wald, arXiv:2311.13482]

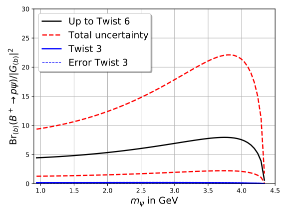
- certain NP models ("Mesogenesis") entertain the possibility of B-meson decays into dark baryons
- described in terms of (model-dependent) 4-fermion operators:
- focus on $B^+ \to p\Psi$: LCSR analysis with nucleon LCDAs (incl. twist-6)



$$-i\,G_{(d)}\,\epsilon_{ijk}\,(\bar{u}^i_R b^{c\,j}_R)(\bar{d}^k_R \psi^c_R) + \text{h.c.}$$



$$-i\,G_{(b)}\,\epsilon_{ijk}\,(\bar{u}^i_R d^{c\,j}_R)(\bar{b}^k_R \psi^c_R) + \text{h.c.}$$



$\to$ substantial uncertainties from higher-twist contributions

$\to$ branching fraction lies within the sensitivity range for Belle-II

Inclusive rates and sum over exclusive channels, semi-inclusive decays

- Mannel, Gubernari, Khodjamirian, Mandal,
  quantitative analysis of rates and decay spectra of $B \to D^{**} \ell \nu$,
  work in progress ...

$\longleftarrow$ input from WA2/WA3

Higher-order QCD corrections

- Huber et al., in the pipeline:
  - calculation of power-suppressed penguin coefficient a_6 in QCDF
  - pheno update of charmless non-leptonics
    (requires better treatment of non-factorizable effects)

1. A. Biswas, S. Descotes-Genon, J. Matias and G. Tetlalmatzi-Xolocotzi,
"A new puzzle in non-leptonic B decays,"
JHEP **06** (2023), 108 [arXiv:2301.10542 [hep-ph]]

2. M. L. Piscopo and A. V. Rusov,
"Non-factorisable effects in the decays $\overline{B}_s^0 \to D_s^+ \pi^-$ and $\overline{B}^0 \to D^+ K^-$ from LCSR,"
JHEP **10** (2023), 180 [arXiv:2307.07594 [hep-ph]].

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more activities:

- E. Malami,
"Theoretical Highlights of CP Violation in B Decays,"
proceedings HQL2023, arXiv:2402.16976 [hep-ph]
- E. Malami,
"Manifestations of CP Violation in the B Meson System: Theoretical Perspective,"
proceedings Beauty2023, arXiv:2402.10023 [hep-ph]
- G. Tetlalmatzi-Xolocotzi,
"QCDF Amplitudes from $SU(3)$ Symmetries,"
proceedings PoS **DISCRETE2022** (2024), 040

also: Huber, Malami, GTX, work in progress

- include $SU(3)_F$ breaking effects:
$(\bar{3} \oplus 6 \oplus \overline{15}) \otimes (1 \oplus 8) = \bar{3} \oplus 6 \oplus \overline{15} \oplus 24 \oplus \overline{42}$
- translation to QCDF amplitudes

A new puzzle in non-leptonic B decays

[A. Biswas, S. Descotes-Genon, J. Matias and G. Tetlalmatzi-Xolocotzi, JHEP **06** (2023), 108]

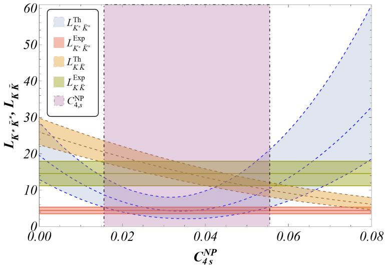
- starting point: ratio of longitudinal amplitudes of two U-spin related decays:

$$L_{K^*\bar{K}^*} = \rho(m_{K^{*0}}, m_{K^{*0}}) \frac{\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \to K^{*0}\bar{K}^{*0})} \frac{f_L^{B_s}}{f_L^{B_d}} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2},$$

(expected to have reduced sensitivity to power corrections in QCDF)

- K^*K^* and KK modes show $\mathcal{O}(2.5\sigma)$ deviations from SM expectations
- could be explained by NP in strong penguins $C_{4,6}$ or chromomagnetic penguin $\mathcal{O}_8^g$

  e.g. variation of $L_{K^*\bar{K}^*}$ and $L_{K\bar{K}}$ w.r.t. $\mathcal{C}_{4s}^{\rm NP}$ $\rightarrow$
- may lead to large deviations for L_{K^*K}



- how sensitive to $SU(3)$ flavour-symmetry breaking ?
- NP interpretation requires inclusion of less robust observables

Coming out soon:

- similar analysis for $B_{s,d} \to K^{(*)}\phi$

Non-factorisable effects in $\overline{B}_s^0 \to D_s^+\pi^-$ and $\overline{B}^0 \to D^+K^-$ from LCSR

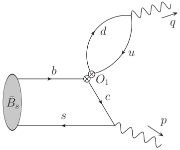
M. L. Piscopo and A. V. Rusov, JHEP **10** (2023), 180

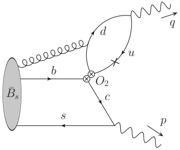
Aim: address factorizable *and* non-factorizable contributions entirely within LCSR framework:

- correlator for non-factorizable contribution

$$\to \langle 0|\mathrm{T}\left\{ j_5^D(x), O_2(0), j_\mu^\pi(y) \right\} |\bar{B}(p+q)\rangle$$

- this work: mixed LC-Local expansion $x^2 \sim 0$, $y^\mu \sim 0$
- alternatively: expansion around two opposite light-ray directions
  $\longrightarrow$ 3-particle soft functions [Huang et al., 2312.15439]





$$\frac{C_2\langle O_2^d\rangle}{C_1\langle O_1^d\rangle} = 0.051^{+0.059}_{-0.052}\,, \qquad (\bar{B}_s^0 \to D_s^+\pi^-)$$

$$\frac{C_2\langle O_2^s\rangle}{C_1\langle O_1^s\rangle} = 0.039^{+0.042}_{-0.034}\,, \qquad (\bar{B}^0 \to D^+K^-)$$

- non-factorizable contributions positive, order of a few percent, significantly larger than in [Bordone et al., 2007.10338]
- resulting BRs are compatible with QCDF and experiment, however, with large uncertainties!

future improvements:

- generic form of 3-particle soft function for all Dirac structures
- hadronic parameters in 2- and 3-particle LCDAs (λ_B, $\lambda_{E,H}^2$)

1. N. Gubernari, M. Reboud, D. van Dyk and J. Virto,
“Dispersive analysis of $B \to K^{(*)}$ and $B_s \to \phi$ form factors,”
JHEP **12** (2023), 153 [arXiv:2305.06301 [hep-ph]]

2. T. Feldmann and N. Gubernari,
”Non-factorisable contributions of strong-penguin operators in $\Lambda_b \to \Lambda \ell^+ \ell^-$”
arXiv:2312.14146 (to appear in JHEP)

3. R. Fleischer, E. Malami, A. Rehult and K. K. Vos,
“New perspectives for testing electron-muon universality,”
JHEP **06** (2023), 033 [arXiv:2303.08764 [hep-ph]]

Dispersive analysis of $B \to K^{(*)}$ and $B_s \to \phi$ form factors

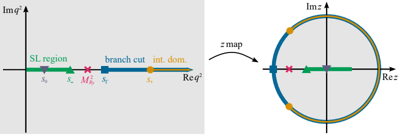
N. Gubernari, M. Reboud, D. van Dyk and J. Virto, JHEP **12** (2023), 153

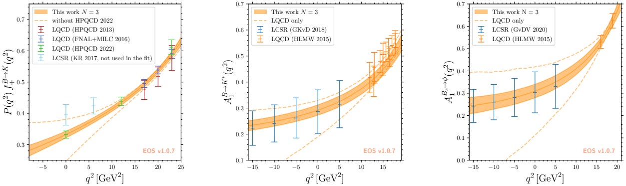
improve on Boyd-Grinstein-Lebed approach:

- invidiual bounds for different helicity projections (λ)

$$\frac{\chi^{(\lambda)}\big|_{1\mathrm{pt}}}{\chi^{(\lambda)}\big|_{\mathrm{OPE}}} + \sum_{\mathcal{F}_\lambda}\sum_{n}\left|a_n^{\mathcal{F}_\lambda}\right|^2 < 1$$

- below-threshold branch-cuts from $B_s\pi$ and $B_s\pi\pi$ accounted for in "z-parametrization"





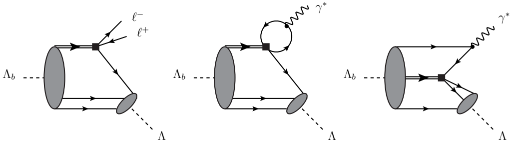
Fit to lattice and sum-rule FFs:

- tighter unitarity bounds
- unwanted correlations removed

$\Rightarrow$ essential improvement for predictions at *negative* (unphysical) values of q^2, important input to the analysis of non-local hadronic matrix elements in $b \to s\ell^+\ell^-$ transitions

Non-factorisable contributions of strong-penguin operators in $\Lambda_b \to \Lambda \ell^+ \ell^-$ (II)

T. Feldmann and N. Gubernari, arXiv:2312.14146 (to appear in JHEP)



- local form factors:

$$\langle \Lambda(p', s') | \bar{s}(0)\, \Gamma\, b(0) | \Lambda_b(p, s) \rangle$$

(for semileptonic operators $\mathcal{O}_{9,10}$)

- "non-local form factors":

$$\langle \Lambda(p', s') | T\left(\mathcal{O}_i(0)\, J_{\rm em}(x)\right) | \Lambda_b(p, s) \rangle$$

(for hadronic penguin operators)

- factorizing quark-loop topologies
- non-factorizing "annihilation-type" of topologies
  $\to q^2$-dependent shifts of Wilson coefficient C_9

$$C_9\, f_+(q^2) \to f_+(q^2) \left(C_9 + \Delta C_{9,+}(q^2)\right) \qquad \text{etc.}$$

estimate of "annihilation" topology with LSCRs: (C2a, see above)

- only operators $\mathcal{O}_5$ and $\mathcal{O}_6$ contribute at leading power
  (opposite to annihilation in mesonic decays)
- transverse photons: $|\Delta C_{9,\perp}|/\Delta C_9 \sim \mathcal{O}(1\%)$ as expected
- longitudinal photons: $\Delta C_{9,+}$ is power-suppressed

	$10^2 \cdot \Delta C_{9,\perp}$
2 GeV^2	$(0.6 \pm 2.5) + i(6.9 \pm 1.3)$
4 GeV^2	$-(0.97 \pm 0.98) + i(1.89 \pm 0.62)$
6 GeV^2	$-(0.64 \pm 0.39) + i(0.63 \pm 0.42)$

- uncertainties dominated by LCDAs of Λ_b

New perspectives for testing electron-muon universality

[R. Fleischer, E. Malami, A. Rehult and K. K. Vos, JHEP **06** (2023), 033]

- recent LHCb results in agreement with electron-muon universality [2212.09152, 2212.09153]

$$\langle R_K \rangle_{[1.1,6.0]} = 0.949 \pm 0.05$$

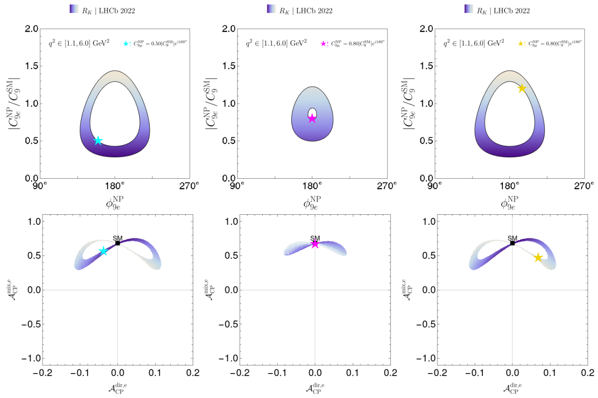
- individual rates still somewhat below SM
- how much space left for LFU violation ?

→ include CP-violating observables in fits
(i.e. allow for complex NP Wilson coefficients)

⇒ *large* differences between CP asymmetries for electron and muon modes are still allowed !

- it would be useful to have a measurement of direct CP violation in R_K, defined by

$$\mathcal{A}_{\rm CP}^{R_K} \equiv \frac{\bar{R}_K - R_K}{\bar{R}_K + R_K},$$



Scenario 1: Constraints on $C_{9e}^{\rm NP}$ for different benchmark points and the corresponding constraints on the CP asymmetries

still plenty of room for electron-muon universality violation!

New perspectives for testing electron-muon universality

- recent LHCb results in agreement with electron-muon universality [2212.09152, 2212.09153]

$$\langle R_K \rangle_{[1.1,6.0]} = 0.949 \pm 0.05$$

- individual rates still somewhat below SM
- how much space left for LFU violation ?

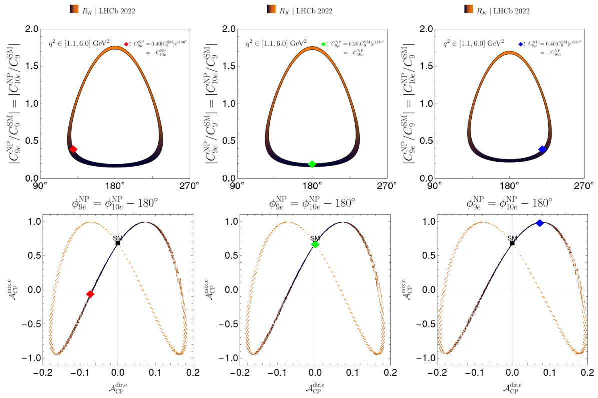
→ include CP-violating observables in fits
(i.e. allow for complex NP Wilson coefficients)

⇒ *large* differences between CP asymmetries for electron and muon modes are still allowed !

- it would be useful to have a measurement of direct CP violation in R_K, defined by

$$\mathcal{A}_{\rm CP}^{R_K} \equiv \frac{\bar{R}_K - R_K}{\bar{R}_K + R_K},$$

[R. Fleischer, E. Malami, A. Rehult and K. K. Vos, JHEP **06** (2023), 033]



Scenario 2: Constraints on $C_{9e}^{\rm NP}$ for different benchmark points and the corresponding constraints on the CP asymmetries

still plenty of room for electron-muon universality violation!

Contributions to Special Topic in EPJC:
”b-Quark Physics as a Precision Laboratory: Present Status and Future Prospects”

1. T. Mannel,
”Introduction to B physics,”,
Eur. Phys. J. Spec. Top. (2023)

2. A. Khodjamirian, B. Melić and Y. M. Wang,
“A guide to the QCD light-cone sum rule for b-quark decays,”
arXiv:2311.08700, published in Eur. Phys. J. Spec. Top. (2023)

3. P. Böer and T. Feldmann,
“Structure-dependent QED effects in exclusive B-meson decays,”
arXiv:2312.12885, published in Eur. Phys. J. Spec. Top. (2024)

Work Areas: Results between 04/23 and 03/24

C2a:

- WA1: Factorization and light-cone distributions ✓✓✓
- WA2: QCD sum rules and related methods ✓✓
- WA3: New channels and multi-hadron final states ✓
- WA4: Inclusive rates and the sum over exclusive channels, semi-inclusive decays X

C2b:

- WA1: Higher-order QCD corrections X
- WA2: Phenomenology of non-leptonic decays ✓✓
- WA3: Phenomenology of rare decays, BSM flavour structures ✓✓✓

$\longrightarrow$ intensify work in C2a/WA4 and C2b/WA1 ...

$\longrightarrow$ initiate more interactions within CRC, in particular in C2b/WA3 $\longrightarrow$ see next slide

Further activities and potential links within the CRC

- V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti and T. Tong,
  "Anomalies in global SMEFT analyses: a case study of first-row CKM unitarity,"
  JHEP **03** (2024) 033, [arXiv:2311.00021 [hep-ph]]
- R. Mandal and T. Tong,
  "Exploring freeze-out and freeze-in dark matter via effective Froggatt-Nielsen theory,"
  JCAP **11** (2023), 074, [arXiv:2307.14972 [hep-ph]]

- Atkinson, Englert, Kirk, Tetlalmatzi-Xolocotzi,
  comparison/interplay between B-physics and top-collider constraints within SMEFT,
  in preparation