Heavy hadron decays: from beauty to charm

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NIKHEF, 13 December 2023

Introduction

The Standard Model . . .

◇ The Standard Model of particle physics (SM)

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + (D_\mu\Phi)^\dagger D^\mu\Phi - V(\Phi^\dagger\Phi) + \left(\bar{\Psi}_L\hat{Y}\Phi\Psi_R + \text{h.c.}\right)$$

- ∗ Quantum field theory of three fundamental forces
- ∗ With Higgs, spectrum of elementary particles complete
- ∗ Numerous successful tests: consistent and predictive theory

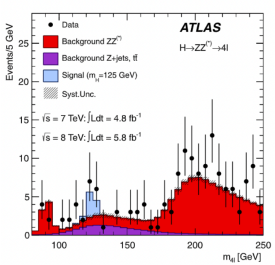
. . . and Beyond

- SM not complete, still many open questions ☹

  Dark matter, baryon asymmetry, . . .

- But how to find new physics (NP)?

Direct searches



limited by energy reachable in particle accelerators ☹

Indirect searches

Compare SM predictions with data:

$$(\mathcal{O} \pm \sigma_{\mathcal{O}})^{\text{Exp}} = (\mathcal{O} \pm \sigma_{\mathcal{O}})^{\text{SM}} + (\mathcal{O} \pm \sigma_{\mathcal{O}})^{\text{NP}}$$

limited by precision in theory and experiments ☹

Why quark flavour physics?

- Excellent route for indirect NP searches
  - Huge number of data has been (and will be) collected

    LHCb, BaBar, BelleII, ATLAS, CMS . . .
  - Theoretical predictions can be systematically improved

    Also test of QCD
  - Study of the structure of CKM matrix

    Connection with CP violation in the SM
  - Maybe already hints of NP e.g. current anomalies in the B-sector

Inclusive B-meson decays

Motivation

- The lifetime $\tau = \Gamma^{-1}$ is a fundamental property of particles
- For heavy hadrons H_Q, systematic framework to compute Γ

$m_Q \gg \Lambda_{QCD}$

- Focus on the B-system
  - Experimental precision very high $\mathcal{O}(‰)$ [HFLAV, PDG]
  - Aim at competitive theoretical precision to both
    - Test the SM and the framework used
    - Perform indirect NP searches

EFTs for heavy hadrons decays

- Weak B-meson decays define multi-scale problem

$$\underbrace{m_W}_{\sim 80 \text{ GeV}} \gg \underbrace{m_b}_{\sim 4.5 \text{ GeV}} \gg \underbrace{\Lambda_{QCD}}_{\sim 0.5 \text{ GeV}}$$

- At scales $\sim m_b$
  - Use weak effective theory (WET) e.g. [Buchalla, Buras, Lautenbacher '96]
  - Observables computed in terms of expansion in $1/m_W^2$
- At scales $\sim \Lambda_{QCD}$
  - Use heavy quark effective theory (HQET) e.g. [Isgur, Wise '89; Georgi '90]
  - Observables computed in terms of expansion in $1/(2m_b)$

The total decay width of a B-meson

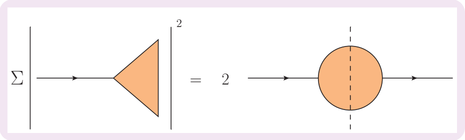
- Start from the definition

$$\Gamma(B) = \frac{1}{2m_B} \sum_n \int_{\rm PS} (2\pi)^4 \delta^{(4)}(p_n - p_B) |\langle n|\mathcal{H}_{eff}|B\rangle|^2$$

- Use optical theorem to rewrite [Shifman, Voloshin '85]

$$\Gamma(B) = \frac{1}{2m_B} {\rm Im} \langle B| i \int d^4x \, {\rm T}\Big\{\mathcal{H}_{eff}(x), \mathcal{H}_{eff}(0)\Big\}|B\rangle$$

- $\mathcal{H}_{eff}$ - weak effective Hamiltonian describing b-quark decays



The heavy quark expansion (HQE)

- The b-quark carries most of the hadron momentum $p_B^\mu = m_B v^\mu$

- Introduce parametrisation

$$p_b^\mu = m_b v^\mu + k^\mu \qquad k \sim \Lambda_{QCD} \ll m_b$$

- Define rescaled b-quark field

$$b(x) = e^{-i m_b v \cdot x}\, b_v(x)$$

- The action of the covariant derivative

$$i D_\mu b(x) = e^{-i m_b v \cdot x} \big(m_b v_\mu + i D_\mu \big) b_v(x)$$

$D_\mu = \partial_\mu - i A_\mu^a(x) t^a$

The HQE

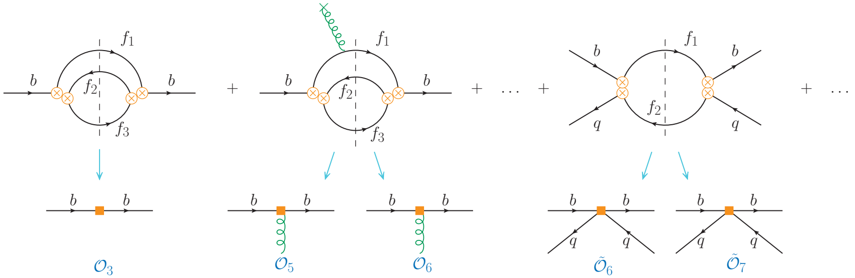
- Obtain systematic expansion

$$\Gamma(B) = \underbrace{\Gamma_3}_{\Gamma(b)} + \underbrace{\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]}_{\delta\Gamma(B)}$$

  - $\Gamma_d, \tilde{\Gamma}_d$ - short distance coefficients
  - $\mathcal{O}_d, \tilde{\mathcal{O}}_d$ - local operators bilinear in the heavy quark field
  - $\Gamma(b)$ - total decay width of free b quark
  - $\delta\Gamma(B)$ - effects due to interaction with soft gluons and quarks

The HQE

$$\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]$$



Very advanced framework thanks to huge effort of big community

Status of the HQE: perturbative side

$$\Gamma_d = \Gamma_d^{(0)} + \left(\frac{\alpha_s(m_b)}{4\pi}\right)\Gamma_d^{(1)} + \left(\frac{\alpha_s(m_b)}{4\pi}\right)^2 \Gamma_d^{(2)} + \dots$$

Semileptonic modes (SL)	
$\Gamma_3^{(3)}$	Fael, Schönwald, Steinhauser '20 Czakon, Czarnecki, Dowling '21
$\Gamma_5^{(1)}$	Alberti, Gambino, Nandi '13 Mannel, Pivovarov, Rosenthal '15
$\Gamma_6^{(1)}$	Mannel, Pivovarov '19
$\Gamma_7^{(0)}$	Dassinger, Mannel, Turczyk '06
$\Gamma_8^{(0)}$	Mannel, Turczyk, Uraltsev '10
$\tilde{\Gamma}_6^{(1)}$	Lenz, Rauh '13

Non-leptonic modes (NL)	
$\Gamma_3^{(2)}$	Czarnecki, Slusarczyk, Tkachov '05 *
$\Gamma_3^{(1)}$	Ho-Kim, Pham '83; Altarelli, Petrarca '91 Bagan et al. '94; Krinner, Lenz, Rauh '13 Lenz, Nierste, Ostermaier '97
$\Gamma_5^{(1)}$	Mannel, Moreno, Pivovarov '23 **
$\Gamma_6^{(0)}$	Lenz, MLP, Rusov '20 Mannel, Moreno, Pivovarov '20
$\tilde{\Gamma}_6^{(1)}$	Beneke, Buchalla, Greub, Lenz, Nierste '02 Franco, Lubicz, Mescia, Tarantino '02
$\tilde{\Gamma}_7^{(0)}$	Gabbiani, Onishchenko, Petrov '03

* Only partial result

** Only massless final states

Status of the HQE: non-perturbative side

	B_d, B^+	B_s
$\langle \mathcal{O}_5 \rangle$	Fits to SL data $^{\diamond}$ Lattice QCD $^{+}$ HQET sum rules *	Spectroscopy relations **
$\langle \mathcal{O}_6 \rangle$	Fits to SL data $^{\diamond}$ EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$	Sum rules estimates ** EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$
$\langle \tilde{\mathcal{O}}_6 \rangle$	HQET sum rules ‡	HQET sum rules ‡
$\langle \tilde{\mathcal{O}}_7 \rangle$	Vacuum insertion approximation	

$^{\diamond}$[Bordone, Capdevila, Gambino '21; Bernlochner, Fael et al. '22; Finauri, Gambino '23]

$^{+}$[Gambino, Melis, Simula '17; Bazavov et al. '18] *[Ball, Braun '94; Neubert '96]

**[Bigi, Mannel, Uraltsev '11] ‡[Kirk, Lenz, Rauh '18; King, Lenz, Rauh '20]

First steps towards extraction of $\langle \mathcal{O}_5 \rangle$ and $\langle \mathcal{O}_6 \rangle$ for B_s from data

[De Cian, Feliks, Rotondo, Vos '23]

The dim-6 two-quark operator contributions

- Sizeable contribution to $\Gamma(B)$ due to Darwin operator

[Lenz, MLP, Rusov '20; Mannel, Moreno, Pivovarov '20]

$$\Gamma(B) = \Gamma_0 \Big[5.53 - 0.14 \frac{\mu_\pi^2(B)}{\text{GeV}^2} - 0.24 \frac{\mu_G^2(B)}{\text{GeV}^2} - 1.35 \frac{\rho_D^3(B)}{\text{GeV}^3} + \ldots \Big]$$

where

$$\rho_D^3(B) = \frac{\langle B | \bar{b}_v (iD_\mu)(iv \cdot D)(iD^\mu) b_v | B \rangle}{2 m_B}$$

- Potential large effect, particularly in $\tau(B_s)/\tau(B_d)$

What is the value of ρ_D^3?

- Tension between different extractions of ρ_D^3 from fits

[Bordone et al, 21; Bernlochner et al. '22; Fael, Gambino '23]

- Alternatively, use EOM for gluon field strength tensor

e.g. [Bigi, Mannel, Uraltsev '11]

$$\mathcal{O}_{\rho_D} = \frac{1}{4m_B}\bar{b}_v[iD_\mu,[iD^\rho,iD^\mu]]v_\rho b_v = -\frac{g_s^2}{4m_B}(\bar{b}_v\gamma^\mu t^a b_v)\sum_q(\bar{q}\gamma_\mu t^a q) + \mathcal{O}\left(\frac{1}{m_b}\right)$$

  - Determine ρ_D^3 from dim-6 four-quark matrix elements
  - However obtain large $SU(3)_F$ breaking effects ~ 50%!

$$\frac{\rho_D^3(B_s)}{\rho_D^3(B_d)} = \frac{f_{B_s}^2\, m_{B_s}}{f_B^2\, m_B} \approx 1.5$$

The observables

- Compute total widths

$$\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]$$

- And lifetime ratios

$$\tau(B_{(s)}^+)/\tau(B_d) = 1 + \left[\delta\Gamma(B_d)^{\rm HQE} - \delta\Gamma(B_{(s)}^+)^{\rm HQE}\right] \tau(B_{(s)}^+)^{\rm exp}$$

- No two-quark contributions for $\tau(B^+)/\tau(B_d)$ in isospin limit

- Crucial role of $SU(3)_F$ breaking effects for $\tau(B_s)/\tau(B_d)$

Results

Scenario A

- Larger inputs for B_d

[Bordone et al. '21]

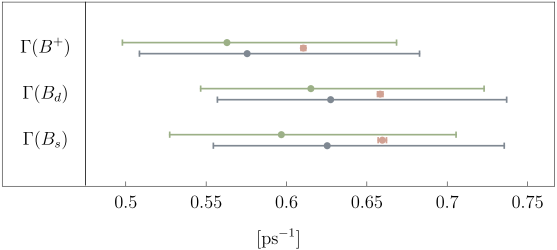
- Larger $SU(3)_F$ breaking

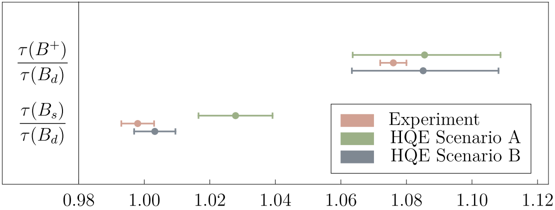
Scenario B

- Smaller inputs for B_d

[Bernlochner et al. '22]

- Smaller $SU(3)_F$ breaking





[Lenz, MLP, Rusov '22]

Results

- Overall good agreement of HQE and data for B-system
- For the total decay widths
  - Large uncertainties, dominated by scale variation in Γ_3

    Only NLO-QCD corrections included so far
  - Crucial the computation of α_s^2-corrections to NL b-decays
- For the ratio $\tau(B^+)/\tau(B_d)$
  - Dominant uncertainties due to four-quark matrix elements

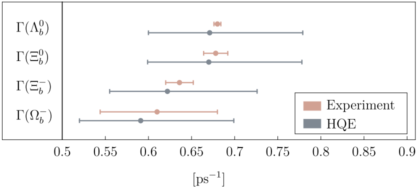
    Lattice determination of bag parameters highly desirable

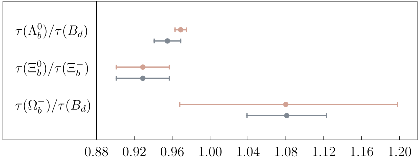
    first steps made [Black, Harlander et al. '23]
- For the ratio $\tau(B_s)/\tau(B_d)$
  - Dominant uncertainties due to two-quark matrix elements
  - Tension with data in one scenario

    Need more information over size of non-pert inputs and $SU(3)_F$ break.

What about other heavy hadrons?

HQE for b-baryons





[Gratrex, Lenz, Melić, Nišandžić, MLP, Rusov '23]

- Very good agreement of HQE predictions with data
- Main sources of uncertainties
  - For total widths: scale variation in leading term Γ_3
  - For lifetime ratios: dim-6 four-quark matrix-elements

No first principle determinations for all baryons, rely on simplified models of QCD

Is the charm quark heavy enough?

- The HQE has two expansion parameters, small for $m_Q \gg \Lambda_{\rm QCD}$
- In the beauty sector

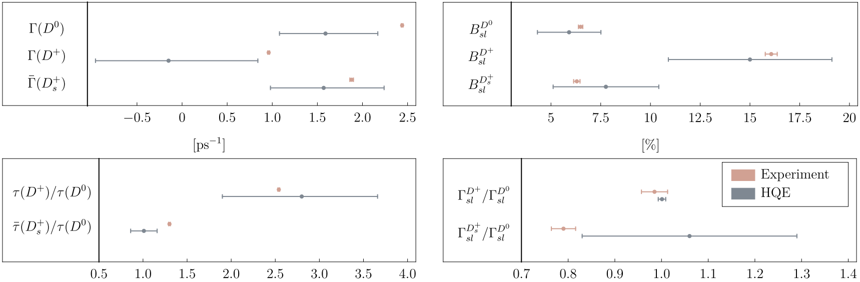
$$\alpha_s(m_b) \sim 0.22 \qquad \frac{\Lambda_{QCD}}{m_b} \sim 0.10$$

- Compare with charm sector

$$\alpha_s(m_c) \sim 0.33 \qquad \frac{\Lambda_{QCD}}{m_c} \sim 0.30$$

  * Applicability of HQE to charm becomes questionable

Test the HQE for charmed hadrons



[King, Lenz, MLP, Rauh, Rusov, Vlahos ’21]

- HQE able to explain observed pattern
- But very large uncertainties, mainly due to
  - Charm quark mass
  - Poorly known non-perturbative inputs

See also e.g. [Gratrex, Melić, Nišandžić ’22; Dulibič, Gratrex, Melić, Nišandžić ’23]

Back to the B-system

B-meson lifetime ratios

- Lifetime ratios are theoretically more clean
- In presence of NP effects

$$\underbrace{\frac{\tau(B^+)}{\tau(B_d)}}_{\text{exp.}} = 1 - \underbrace{\tau(B^+)\left[\delta\Gamma(B^+) - \delta\Gamma(B_d)\right]^{\text{HQE}}}_{\text{theory}} - \underbrace{\tau(B^+)\left[\delta\Gamma(B^+) - \delta\Gamma(B_d)\right]^{\text{NP}}}_{\text{indirectly constrained}}$$

- Potential to constrain certain BSM operators
- Mainly limited by theory uncertainties
- Until further insights on $\tau(B_s)/\tau(B_d)$, use only $\tau(B^+)/\tau(B_d)$

However larger uncertainties!

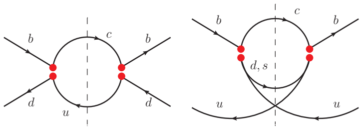
BSM effects in $\tau(B^+)/\tau(B_d)$ and mixing

- Observed tensions in hadronic B-decays triggered by $b \to c\bar{u}d(s)$

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

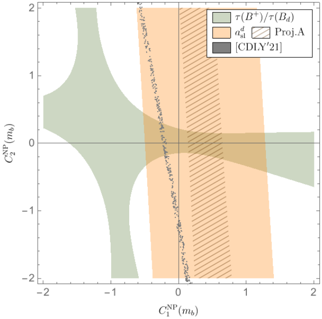
  - How large is space for NP in $b \to c\bar{u}d(s)$ decays ?
  - Repeat computation with 20 additional NP operators, also for a_{sl}^d

$$\mathcal{H}_{eff} = \mathcal{H}_{eff}^{\rm SM} + \mathcal{H}_{eff}^{\rm NP}$$



Compare with study of decays like $\bar{B}_s \to D_s^+ \pi^-$

[Cai, Deng, Li, Yang '21]



[Lenz, Müller, MLP, Rusov '22]

Conclusions *(for lifetimes)*

- Up-to-date analysis of heavy hadron lifetimes within HQE
- Good agreement with data but mostly larger uncertainties
- Big room for improvement
  - Higher order QCD corrections e.g. $\Gamma_3^{(2)}, \tilde{\Gamma}_6^{(2)}$

    Planned by U. Nierste, M. Steinhauser et al. in Karlsruhe
  - Determination of $\langle \tilde{O}_6 \rangle$ by lattice QCD

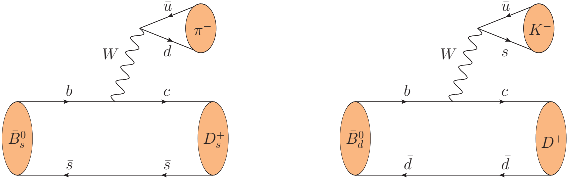
    Planned by O. Witzel, M. black in Siegen
  - Better control on two-quark non-perturbative inputs

    Crucial impact on $\tau(B_s)/\tau(B_d)$
- With higher precision, potential to constrain some NP operators

Hadronic B-meson decays from Light-Cone Sum Rules (LCSR)

[Balitsky, Braun, Kolesnischenko '89]

The decays $\bar{B}^0 \to D^+K^-$ *and* $\bar{B}^0_s \to D^+_s\pi^-$



- Tree-level decays induced by $b \to c\bar{u}d(s)$ transitions

- Theoretically "clean" channels

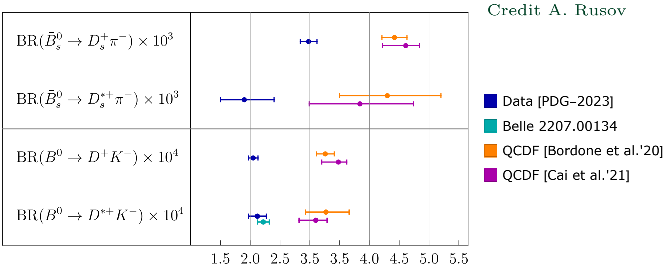
  No pollution due to penguin and annihilation topologies

- Golden modes for QCD factorisation (QCDF) framework

  [Beneke, Buchalla, Neubert, Sachrajda '99 -'01]

A puzzling pattern

◇ Tension between QCDF predictions and data ranging $(2-7)\,\sigma$



⋆ QED corrections? Rescattering effects?

[Beneke, Böer, Finauri, Vos '21; Endo, Iguro, Mishima '21]

⋆ Investigated potential BSM scenarios

e.g. [Iguro, Kithara '20; Cai, Deng, Li, Yang '21; Fleischer, Malami '21; Lenz et al. '22]

⋆ Interplay with collider constraints [Bordone, Greljo, Marzocca '21]

Status of power corrections

- Systematic study of power corrections challenging in QCDF
- First estimates of $\mathcal{O}(\Lambda_{\text{QCD}}/m_b)$ contributions

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

  - Computed non-factorisable soft-gluon exchange within LCSR
  - Found very small effect

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

- Can we obtain an alternative estimate?

The decay amplitude

- Use the weak effective Hamiltonian

$$\mathcal{A}(\bar{B}_s^0 \to D_s^+ \pi^-) = -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} \Big[C_1 \langle O_1 \rangle + C_2 \langle O_2 \rangle \Big]$$

$$O_1 = \big(\bar{c}\gamma_\mu(1-\gamma_5)b\big)\big(\bar{d}\gamma^\mu(1-\gamma_5)u\big) \qquad O_2 = \big(\bar{c}\gamma_\mu(1-\gamma_5)t^a b\big)\big(\bar{d}\gamma^\mu(1-\gamma_5)t^a u\big)$$

- In naive QCDF

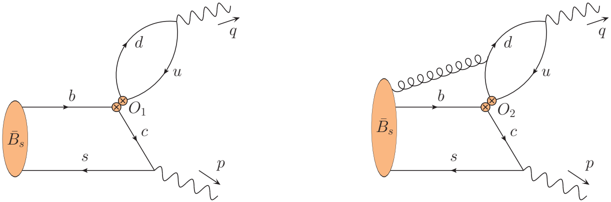
$$\langle O_1 \rangle \overset{\text{NQCDF}}{=} i f_\pi (m_{B_s}^2 - m_{D_s}^2) f_0^{B_s D_s}(m_\pi^2) \qquad \langle O_2 \rangle \overset{\text{NQCDF}}{=} 0$$

- First estimate of $\langle O_2 \rangle$ beyond NQCDF using two-point sum rule

[Blok, Shifman '93]

$$C_2 \langle O_2 \rangle / C_1 \langle O_1 \rangle \sim 13\%$$

New estimate of decay amplitude using LCSR



- Start from three-point correlation function see e.g. [Khodjamirian '00]

$$\mathcal{F}_\mu^{O_i}(p,q) = i^2 \int d^4x \int d^4y \; e^{ip\cdot x} e^{iq\cdot y} \, \langle 0 | T\{ j_5^D(x), \, O_i(0), j_\mu^\pi(y) \} | \bar{B}(p+q) \rangle$$

$$j_5^D(x) = i m_c (\bar{s}\gamma_5 c)(x) \qquad j_\mu^\pi(y) = (\bar{u}\gamma_\mu\gamma_5 d)(y)$$

Light-cone OPE for the correlation functions

- Consider kinematical region of p^2, q^2 large and negative

- Dominant contribution from

$$x^2 \sim 0 \qquad y^2 \sim 0 \qquad (x-y)^2 \nsim 0$$

x and y are aligned along different light-cone directions!

- Double LC expansion of correlator $\mathcal{F}_\mu^{O_2}$ not feasible

$$\langle 0|\bar{q}(z_1 n) G_{\mu\nu}(z_2 \bar{n}) h_v(0)|\bar{B}(v)\rangle = ?$$

see [Belov, Berezhnoy, Melikhov '23]

$v^\mu = (n^\mu + \bar{n}^\mu)/2$ $\quad$ $n^\mu = (1,0,0,1)$ $\quad$ $\bar{n}^\mu = (1,0,0,-1)$

- Expand instead around $x^2 \sim 0$ but $y^\mu \sim 0$

Light-cone OPE for the correlation functions

- For light-quark loop use local expansion of propagator up to $G_{\mu\nu}$

e.g. [Balitsky, Braun '89]

$$S_{ij}^{(q)}(x,y) = \int \frac{d^4k}{(2\pi)^4} e^{-ik(x-y)} \left[\frac{\delta_{ij}\, \not{k}}{k^2 + i\varepsilon} - \frac{G^a_{\alpha\beta} t^a_{ij}}{4} \frac{(\not{k}\,\sigma^{\alpha\beta} + \sigma^{\alpha\beta}\not{k})}{(k^2 + i\varepsilon)^2} \right] + \ldots$$

- Use 2- and 3-particle B-meson LCDAs up to twist-six

[Braun, Ji, Manashov '17]

$$\langle 0|\bar{q}(x) G_{\mu\nu}(0) h_v(0)|\bar{B}(v)\rangle \sim \int_0^\infty d\omega_1\, e^{-i\omega_1 v\cdot x} f_{\mu\nu}\big(\{\phi_3, \phi_4, \ldots, \phi_6\}(\omega_1)\big)$$

$$\langle 0|\bar{q}(x) h_v(0)|\bar{B}(v)\rangle \sim \int_0^\infty d\omega\, e^{-i\omega v\cdot x} f\big(\{\phi_+, \phi_-, g_+, g_-\}(\omega)\big)$$

The OPE results

- Both correlators take the form

$$\mathcal{F}_\mu^{O_i} = \left(q_\mu(p\cdot q) - p_\mu q^2\right)\mathcal{F}^{O_i}(p^2, q^2)$$

  - Result transversal with respect to q^μ

- Arrive at final OPE for the invariant amplitudes

$$[\mathcal{F}_q^{O_2}(p^2,q^2)]_{\text{OPE}} \sim \int_0^\infty d\omega_1 \sum_{\psi=\phi_3,\ldots} \psi(\omega_1) \sum_{n=1}^{3} \frac{c_n^\psi(\omega_1,q^2)}{\left[\tilde{s}(\omega_1,q^2) - p^2 - i\varepsilon\right]^n}$$

  - Similarly for $\mathcal{F}_q^{O_1}$ - including both 2- and 3-particle contributions

Link OPE to hadronic matrix element

- Derive double dispersion relations in p^2- and q^2-channels
- Approximate continuum using quark-hadron duality (QHD)
- Obtain final sum-rule for matrix element

$$i\langle O_2\rangle = \frac{1}{f_\pi f_D m_D^2 \pi^2} \int_0^{s_0^\pi} ds' \int_{m_c^2}^{s_0^D} ds \; \mathrm{Im}_{s'} \mathrm{Im}_s \left[\mathcal{F}_q^{O_2}(s,s')\right]_{\mathrm{OPE}} e^{(m_\pi^2 - s')/M'^2} e^{(m_D^2 - s)/M^2}$$

  - Sum-rule parameters $s_0^\pi, s_0^D, M^2, M'^2$ to be determined

Results

- For the ratios of non-factorisable over factorisable contributions

$$\frac{C_2\langle O_2^d\rangle}{C_1\langle O_1^d\rangle} = 0.051^{+0.059}_{-0.052} \qquad \frac{C_2\langle O_2^s\rangle}{C_1\langle O_1^s\rangle} = 0.039^{+0.042}_{-0.034}$$

[MLP, Rusov '23]

- For the branching ratios

$$\mathcal{B}(B_s^0 \to D_s^- \pi^+)|_{\text{exp.}} = (2.98 \pm 0.14) \times 10^{-3} \qquad \mathcal{B}(B^0 \to D^- K^+)|_{\text{exp.}} = (2.05 \pm 0.08) \times 10^{-4}$$

$$\mathcal{B}(\bar{B}_s^0 \to D_s^+ \pi^-)|_{\text{SM}} = (2.15^{+2.14}_{-1.35}) \times 10^{-3} \qquad \mathcal{B}(\bar{B}^0 \to D^+ K^-)|_{\text{SM}} = (2.04^{+2.39}_{-1.20}) \times 10^{-4}$$

[MLP, Rusov '23]

- Large uncertainties mainly due to parameters of B-meson LCDAs

Conclusions *(for NL B-meson decays)*

- New study of the decays $\bar{B}^0_{(s)} \to D^+_{(s)} K^- (\pi^-)$ with LCSR

- Estimate fact. and non-fact. contributions with same framework

  Alternative to QCDF, currently still larger uncertainties

- Non-factorisable contributions found to be large (but positive)

- Many inputs for the B-meson still poorly constrained!

- New insights might come using the light-meson LCDAs

  More precisely known

Two-body non-leptonic D^0-meson decays from LCSR

CP violation in charm sector

- Discovery of CP violation in D^0 decays by LHCb [arXiv:1903.08726]

$$\Delta A_{\rm CP} \equiv A_{\rm CP}(K^-K^+) - A_{\rm CP}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

$$\Delta a_{\rm CP}^{\rm dir.} = (-15.7 \pm 2.9) \times 10^{-4}$$

- New data by LHCb on $A_{\rm CP}(K^-K^+)$
  - Combination with $\Delta A_{\rm CP}$ gives [arXiv:2209.03179]

$$a_{\rm CP}^{\rm dir.}(K^-K^+) = (7.7 \pm 5.7) \times 10^{-4} \qquad a_{\rm CP}^{\rm dir.}(\pi^-\pi^+) = (23.2 \pm 6.1) \times 10^{-4}$$

$$a_{\rm CP}^{\rm dir.}(f) \equiv \frac{\Gamma(\overline{D}^0(t) \to \bar{f}) - \Gamma(D^0(t) \to f)}{\Gamma(\overline{D}^0(t) \to \bar{f}) + \Gamma(D^0(t) \to f)}$$

Theory status so far

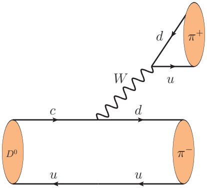
- Determination of $\Delta a_{CP}^{dir.}$ from LCSR largely deviates from data
  [Khodjamirian, Petrov '17]
  - Triggered NP interpretations e.g. [Chala, Lenz, et al. '19; Dery, Nir '19]

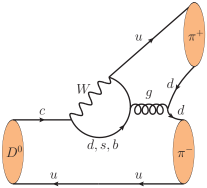
- Recent study of rescattering effects using dispersive methods
  - Results for CP violation still below the experimental values
    [Pich, Solomonidi, Vale Silva '23]

- Also potential explanations of ΔA_{CP}
  - Using U-spin relations and $SU(3)_F$ symmetry e.g. [Grossman, Schacht '19]

    However, opposite sign for CP asymmetries, "U-spin anomaly"
    e.g. [Bause, Gisbert, Hiller et al. '22; Schacht '23]
  - From analyses of topological amplitudes, or final state interactions
    e.g. [Li, Lü, Yu '19; Cheng, Chiang '19; Bediaga, Frederico, Megahlães '22]

The decay $D^0 \to \pi^-\pi^+$ *(and similarly for* $D^0 \to K^-K^+$*)*





◇ Theoretically very challenging, different topologies contribute

$$\mathcal{A}(D^0 \to \pi^-\pi^+) = \lambda_d(\mathcal{A}_{tree} + \mathcal{A}^d_{peng.}) + \lambda_s \mathcal{A}^s_{peng.} + \lambda_b \mathcal{A}^b_{peng.}$$

$\lambda_q = V^*_{cq} V_{uq}$

◇ From unitarity of CKM $\lambda_d + \lambda_s + \lambda_b = 0$

$$\mathcal{A}(D^0 \to \pi^-\pi^+) = \lambda_d \, \mathcal{A}_{\pi\pi} \left(1 - \frac{\lambda_b}{\lambda_d} \frac{\mathcal{P}_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right)$$

The decay $D^0 \to \pi^-\pi^+$ *(and* $D^0 \to K^-K^+$*)*

- Using $\lambda_b/\lambda_d \ll 1$, the branching ratio becomes

$$\mathcal{B}(D^0 \to \pi^-\pi^+) \simeq |\lambda_d|^2 |\mathcal{A}_{\pi\pi}|^2$$

- And the CP asymmetry

$$a_{\rm CP}^{\rm dir}(\pi^-\pi^+) \simeq 2\left|\frac{\lambda_b}{\lambda_d}\right| \sin\gamma \left|\frac{\mathcal{P}_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right| \sin\phi_{\pi\pi}$$

  - Sensitive to difference of weak and strong phases γ, $\phi_{\pi\pi}$, and $\left|\frac{\mathcal{P}_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right|$

- Similarly for $a_{\rm CP}^{\rm dir.}(K^-K^+)$, but with opposite sign due to $\lambda_s \approx -\lambda_d$

The decays within LCSR

- Estimate of $\Delta a_{\rm CP}^{\rm dir.}$ in the SM [Khodjamirian, Petrov '17]
  - Computed penguin contributions $\mathcal{P}_{\pi\pi}, \mathcal{P}_{KK}$, with LCSR
  - Used experimental values for $\mathcal{B}$ to extract $|\mathcal{A}_{\pi\pi}|$, $|\mathcal{A}_{KK}|$

$$\mathcal{B}(D^0 \to \pi^-\pi^+)|_{\rm exp.} = (1.454 \pm 0.024) \times 10^{-3}$$

$$\mathcal{B}(D^0 \to K^-K^+)|_{\rm exp.} = (4.08 \pm 0.06) \times 10^{-3}$$

  - Obtained $|\Delta a_{\rm CP}^{\rm dir.}|_{\rm SM} \leq 2.3 \times 10^{-4}$

- Determine also $|\mathcal{A}_{\pi\pi}|$, $|\mathcal{A}_{KK}|$, using LCSR [Lenz, MLP, Rusov (to appear)]
  - First step, only leading contribution
  - Important test of the framework adopted
  - Very promising results

Conclusions *(for NL D-meson decays)*

- Recent discovery of CP violation in D^0-decays
- Solid SM predictions necessary for a clear interpretation of data
  - Computed leading penguin contributions with LCSR
    [Khodjamirian, Petrov '17]
  - Use LCSR to also predict the branching ratios
    [Lenz, MLP, Rusov (to appear)]
    - Determine $\Delta a_{\text{CP}}^{\text{dir.}}$ within the same framework
      Significant reduction of theory uncertainties
    - First step, additional contributions can be systematically included

Thanks for the attention