The non-leptonic $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}(\pi^-, K^-)$ *decays: experiment and theory*

Maria Laura Piscopo

CPPS, Theoretische Physik 1, Universität Siegen

Nicole Skidmore

University of Warwick

"Beyond the Flavour Anomalies V"

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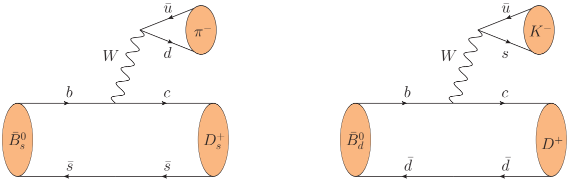
A new anomaly?

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



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

- Theoretically “clean” channels

  No pollution due to penguin and annihilation topologies

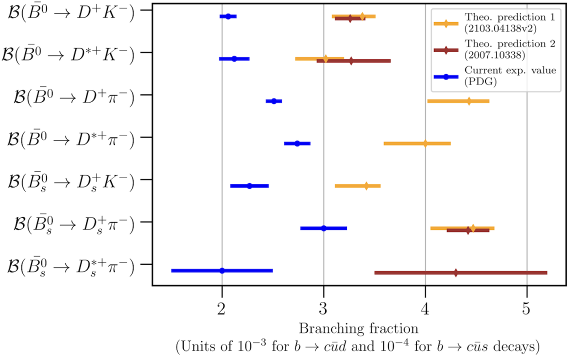
- Golden modes for QCD factorisation (QCDF) framework

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

A puzzling pattern

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

[Bordone, Gubernari, Huber, Jung, van Dyk '20; Cai, Deng, Li, Yang '21]



New Belle data [2207.00134] not yet included in the average

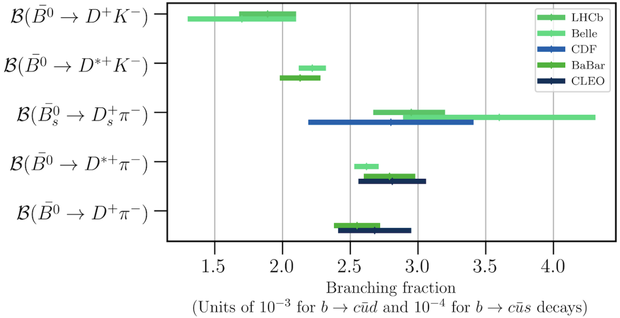
Could this be an experimental issue?

- Unlikely, results consistent across multiple experiments

Also in different collision environments (pp, e^+e^-)

  - Would represent a systematic $\approx 30\%$ downward shift in the data

In channels which are experimentally well accessible



Closer look at QCDF predictions

◇ Starting from the factorisatrion formula

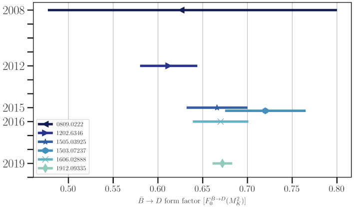
$$\langle O_i^q \rangle \Big|_{\mathrm{QCDF}} = \sum_j f_j^{B_{(s)} D_{(s)}}(m_L^2) \int_0^1 du\, T_{ij}(u) \varphi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)$$

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

- $T_{ij}(u)$ known up to NNLO-QCD corrections [Huber, Kränkl, Li '16]
- Form factors obtained from combination of QCD sum rules and Lattice results

[Bordone, Gubernari, Jung, van Dyk '19]

See also yesterday afternoon session



Status of power corrections

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

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

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

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

*Light-cone sum rules [Balitsky, Braun, Kolesnischenko '89]

Clear theory interpretation still missing

- Studied QED corrections, rescattering effects, but not sufficient

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

- Power corrections may be underestimated [MLP, Rusov '23]

- Data well described with $\mathrm{SU}(3)_F$ breaking effects of ~ 20%

  [Davies, Schacht, NS, Soni '24]

- Investigated possible BSM contributions in tree-level b-decays

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

  - Potential sizeable effects in γ, lifetime and mixing observables

    [Lenz, Tetlalmatzi-Xolocotzi '19; Lenz, Müller, MLP, Rusov '22]

  - Also strong interplay with collider constraints

    [Bordone, Greljo, Marzocca '21]

Experimental status and future prospects

LHCb prospects for branching fraction precision

- Measurements of $\mathcal{B}$ depend on fragmentation fractions f_q $q = d, s$
- Observed dependency between particle multiplicity and f_q

  LHCb [2204.13042]; ALICE [2105.06335]

  - Quark coalescence as possible hadronisation mechanism

    Alternative to fragmentation at low p_T and high multiplicity

  - f_q not universal among collision environments

    Conservative assumptions must be -and have been- made to form global analyses

- Multiple data on $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} h^-$ from single experiment needed

  To reduce sensitivity to $B_{(s)}$-meson production

LHCb prospects for branching fraction precision

- $\mathcal{B}$ measured relative to $\bar{B}^0 \to D^+\pi^-$ normalisation channel

  To cancel luminosity/cross-sections dependence

  - Uncertainty on this mode leads to limiting external systematic

    Also affected by tension

- Previously at LHCb hadronic normalisation channel necessary

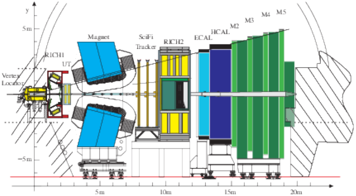
  Poor knowledge of L0 trigger efficiency

  - Leading to dominant systematic uncertainty

LHCb prospects for branching fraction precision

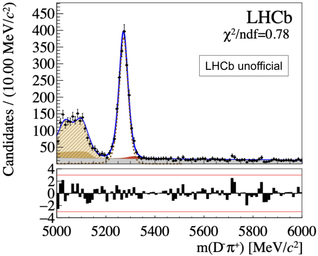
◇ With U1's fully software trigger, able to use leptonic channels

With better known branching fraction



∗ $\mathcal{B}(\bar{B}^{+} \to J/\Psi K^{+})$ has 1.9% uncertainty

∗ With Run 3 data achievable factor 4 increase in sensitivity for $\bar{B}^{0} \to D^{(*)+}h^{-}$



∗ Run 3 data at 14fb^{-1} will be 2 - 3 × more efficient for hadronic decays than Run 2

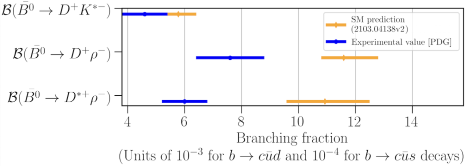
← Mass distribution for $\bar{B}^{0} \to D^{+}\pi^{-}$ using 47pb^{-1} of data taken in 2023 with VELO open

LHCb prospects for branching fraction precision

◇ Hints of tension also in modes with associated vector meson

⋆ Reconstructed decay has a neutral particle

Harder to measure at LHCb

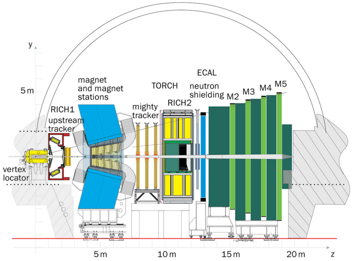


⋆ LHCb U2 (2035) will operate at 10× instantaneous luminosities

⋆ Minimum dataset of 300 fb^{-1}

⋆ Improvements to the ECAL granularity and energy resolution, as well as unprecedented sensitivity to these modes

LHCb [1808.08865]



LHCb prospects for BSM searches in tree-level decays

- Consider the CP asymmetry, defined as

$$A_{\rm fs}^q = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

- $A_{\rm fs}^q$ can provide clear test of BSM effects in tree-level NL decays

  - In the SM, for $\bar{B}^0 \to D^+ K^-$ and $\bar{B}_s \to D_s^+ \pi^-$, $A_{\rm fs}^q = a_{\rm fs}^q$

    Asymmetry only due to CPV in mixing

$$a_{\rm sl}^d = a_{\rm fs}^d \overset{\rm exp}{=} (-21 \pm 17) \cdot 10^{-4} \qquad a_{\rm sl}^s = a_{\rm fs}^s \overset{\rm exp}{=} (-60 \pm 280) \cdot 10^{-5}$$

[PDG '23]

  - In generic BSM scenarios, contribution from direct CPV, $A_{\rm fs}^q \neq a_{\rm fs}^q$
    - The CP asymmetry may be enhanced up to $\mathcal{O}(10^{-2})$

      [Gershon, Lenz, Rusov, NS '21; Fleischer, Vos '17]
    - $A_{\rm fs}^q$ has never been measured for these modes

LHCb prospects for BSM searches in tree-level decays

- Exp. favourable to measure untagged, time integrated asymmetry

$$\langle A^q_{\text{untagged}} \rangle \approx A^q_{\text{dir}} - \frac{a^q_{\text{fs}}}{2}(1-\rho_q)$$

($\rho_d \approx 0.63$ and $\rho_s \approx 0.001$)

  - Flavour tagging efficiency at LHCb $\approx 6\%$

Untagged method provides greater sensitivity

  - Better sensitivity and experimental prospects for $\bar{B}_s \to D_s^+ \pi^-$

Compared to $\bar{B}^0 \to D^+ K^-$ due to higher mixing frequency

$$\langle A^s_{\text{untagged}} \rangle \approx A^s_{\text{dir}} - \frac{a^s_{\text{fs}}}{2}$$

  - Run 2 measurement ongoing with predicted sensitivity of 2×10^{-3}
  - Run 3 will provide sensitivity of 6×10^{-4}

With unprecedented samples of B_s decays

Possibility to clearly identify BSM effects or severely constrain them in these decays

Hadronic B-meson decays from LCSR

Based on arXiv:2307.07594
in collaboration with A. Rusov

The decay amplitude

- Use the weak effective Hamiltonian

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

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

- In naive QCDF

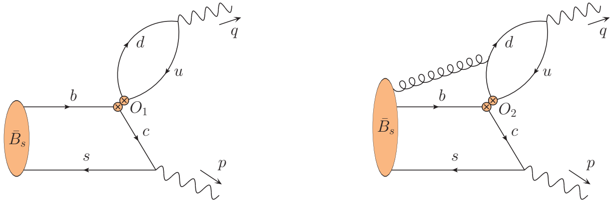
$$\langle O_1 \rangle \overset{\text{NQCDF}}{=} i f_\pi (m_{B_s}^2 - m_{D_s}^2) f_0^{B_s D_s}(m_\pi^2) \qquad \langle O_2 \rangle \overset{\text{NQCDF}}{=} 0$$

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

[Blok, Shifman '93]

$$C_2 \langle O_2 \rangle / C_1 \langle O_1 \rangle \sim 8\%$$

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 to correlator 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 $\mathcal{F}_\mu^{O_2}$ requires*

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

e.g. [Belov, Berezhnoy, Melikhov '23; Qin, Shen, Wang, Wang '22]

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

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

* see also [Feldmann, Gubernari '23]

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]

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

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

[Braun, Ji, Manashov '17]

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

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

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

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

  - 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
- 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

Input parameters

- Use exponential model for LCDAs
  - For $\phi_+, \phi_-, g_+, \phi_3, \phi_4, \tilde{\psi}_4, \psi_4$ use models from [Braun, Ji, Manashov '17]
  - For $g_-, \tilde{\phi}_5, \psi_5, \tilde{\psi}_5, \phi_6$ use models from [Lü, Shen, Wang, Wei '18]
  - Inclusion of $\tilde{\phi}_5, \ldots \psi_6$ necessary to preserve local limit of 3p ME

Also lift of some cancellations between LCDAs!

- Main limitations due to poorly known input parameters
  - Dominant uncertainty coming from λ_H^2, λ_B

Results

- For the ratios of non-factorisable over factorisable contributions

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

  - Non-factorisable corrections found large but positive!

- For the branching ratios

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

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

Conclusions

- With U1 LHCb can significantly improve precision for $\mathcal{B}$

  And make measurements to clearly identify/constrain BSM effects

- New estimate of fact. and non-fact. contributions with LCSR

  Alternative to QCDF, currently still larger uncertainties

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

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

    Recent progress on determination of $\lambda_{B_d}, \lambda_{B_s}$ using Lattice inputs

    [Mandal, Nandi, Ray '23; Mandal, Patil, Ray '24]

  * New insights might come using the light-meson LCDAs

    Which are more precisely known

Thanks for the attention