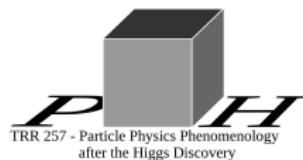


The Λ_b fragmentation fraction from hadronic decays

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Bordone, Gubernari, Jung, van Dyk, TH 2007.10338 (EPJC) and in progress

b-baryon workshop, Orsay / virtual, November 5th – 6th, 2020

Outline

- Motivation and idea
- Mesonic case
 - QCD factorization and leading-power results
 - Power corrections
- Baryonic case
- Conclusion

Fragmentation fractions

- Many observables including B_s mesons and Λ_b baryons are accessible at hadron colliders
 - Significant source of uncertainty:
 b -quark fragmentation fractions f_s/f_d and f_{Λ_b}
 - Fragmentation fractions usually determined using semileptonic decays
- Idea
 - Determine b -quark fragmentation fractions from hadronic two-body decays into heavy-light final states
 - For mesons (baryons see later)

[Fleischer,Serra,Tuning'10]

$$\frac{\sigma(pp \rightarrow \bar{B}_s^0 X) \times \mathcal{B}(\bar{B}_s^0 \rightarrow D_s^{(*)+} \pi^-)}{\sigma(pp \rightarrow \bar{B}^0 X) \times \mathcal{B}(\bar{B}^0 \rightarrow D^{(*)+} K^-)}$$

$$\mathcal{R}_{s/d}^{P(V)} \equiv \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_s^{(*)+} \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)+} K^-)}$$

- Well-established framework for non-leptonic decays [Beneke,Buchalla,Neubert,Sachrajda'99-'04]

$$\langle D_q^{(*)+} L^- | \mathcal{Q}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \rightarrow D_q^{(*)}}(M_L^2) \int_0^1 du T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)$$

- Particularly clean for heavy-light final states
 - Only colour-allowed tree amplitude
 - No colour-suppressed tree amplitude, no penguins
 - Spectator scattering and weak annihilation power suppressed
 - Weak annihilation absent if all final-state flavours distinct
 - as in $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$ and $\bar{B}^0 \rightarrow D^+ K^-$ but not in $\bar{B}^0 \rightarrow D^+ \pi^-$

Leading power

- Amplitudes to leading power in $\epsilon \sim \Lambda_{\text{QCD}}/E_L \sim \Lambda_{\text{QCD}}/m_b$

$$\mathcal{A}(\bar{B}_q^0 \rightarrow D_q^+ L^-) = i \frac{G_F}{\sqrt{2}} V_{uq_2}^* V_{cb} f_L \color{red}{a_1(D_q^+ L^-)} F_0^{\bar{B}_q \rightarrow D_q}(M_L^2) (M_{B_q}^2 - M_{D_q}^2)$$

$$\mathcal{A}(\bar{B}_q^0 \rightarrow D_q^{*+} L^-) = -i \frac{G_F}{\sqrt{2}} V_{uq_2}^* V_{cb} f_L \color{red}{a_1(D_q^{*+} L^-)} A_0^{\bar{B}_q \rightarrow D_q^*}(M_L^2) 2M_{D_q^*} \epsilon^*(\lambda=0) \cdot q$$

- a_1 is the color-allowed tree amplitude, known to $\mathcal{O}(\alpha_s^2)$

[Kräckl,Li,TH'16]

- F_0 and A_0 are $\bar{B}_q \rightarrow D_q$ and $\bar{B}_q \rightarrow D_q^*$ form factors

- Recent precision study in the framework of HQE, using lattice calculations and Light-Cone sum rules

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

Leading power

- Ratio of branching ratios to leading power

$$\mathcal{R}_{s/d}^P = \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_s^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ K^-)} = \frac{\tau_{B_s}}{\tau_{B_d}} \left| \frac{V_{ud}}{V_{us}} \right|^2 \frac{f_\pi^2}{f_K^2} \left| \frac{F_0^{\bar{B}_s \rightarrow D_s}(M_\pi^2)}{F_0^{\bar{B} \rightarrow D}(M_K^2)} \right|^2 \left| \frac{a_1(D_s^+ \pi^-)}{a_1(D^+ K^-)} \right|^2 \\ \times \left(\frac{M_{B_s}^2 - M_{D_s}^2}{M_B^2 - M_D^2} \right)^2 \frac{M_B^3}{M_{B_s}^3} \frac{\sqrt{\lambda(M_{B_s}^2, M_{D_s}^2, M_\pi^2)}}{\sqrt{\lambda(M_B^2, M_D^2, M_K^2)}}$$

$$\mathcal{R}_{s/d}^V = \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_s^{*+} \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} K^-)} = \frac{\tau_{B_s}}{\tau_{B_d}} \left| \frac{V_{ud}}{V_{us}} \right|^2 \frac{f_\pi^2}{f_K^2} \left| \frac{A_0^{\bar{B}_s \rightarrow D_s^*}(M_\pi^2)}{A_0^{\bar{B} \rightarrow D^*}(M_K^2)} \right|^2 \left| \frac{a_1(D_s^{*+} \pi^-)}{a_1(D^{*+} K^-)} \right|^2 \\ \times \frac{M_B^3}{M_{B_s}^3} \frac{[\lambda(M_{B_s}^2, M_{D_s^*}^2, M_\pi^2)]^{3/2}}{[\lambda(M_B^2, M_{D^*}^2, M_K^2)]^{3/2}}$$

Leading power

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- Tree amplitudes

| | | | |
|-------------------------|---|------------------------------|---|
| $ a_1(D_s^+ \pi^-) $ | — | $1.0727^{+0.0125}_{-0.0140}$ | $\left \frac{a_1(D_s^+ \pi^-)}{a_1(D^+ K^-)} \right = 1.0024^{+0.0023}_{-0.0011}$ |
| $ a_1(D^+ K^-) $ | — | $1.0702^{+0.0101}_{-0.0128}$ | |
| $ a_1(D_s^{*+} \pi^-) $ | — | $1.0713^{+0.0128}_{-0.0137}$ | |
| $ a_1(D^{*+} K^-) $ | — | $1.0687^{+0.0103}_{-0.0125}$ | $\left \frac{a_1(D_s^{*+} \pi^-)}{a_1(D^{*+} K^-)} \right = 1.0024^{+0.0023}_{-0.0011}$ |

Leading power

- Ratio of branching ratios to leading power

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$$\times \left(\frac{M_{B_s}^2 - M_{D_s}^2}{M_B^2 - M_D^2} \right)^2 \frac{M_B^3}{M_{B_s}^3} \frac{\sqrt{\lambda(M_{B_s}^2, M_{D_s}^2, M_\pi^2)}}{\sqrt{\lambda(M_B^2, M_D^2, M_K^2)}}$$

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$$\times \frac{M_B^3}{M_{B_s}^3} \frac{[\lambda(M_{B_s}^2, M_{D_s^*}^2, M_\pi^2)]^{3/2}}{[\lambda(M_B^2, M_{D^*}^2, M_K^2)]^{3/2}}$$

Form factors

| | | | |
|--|---|-------------------|---|
| $F_0^{\bar{B} \rightarrow D}(M_K^2)$ | — | 0.672 ± 0.011 | $\left \frac{F_0^{\bar{B}_s \rightarrow D_s}(M_\pi^2)}{F_0^{\bar{B} \rightarrow D}(M_K^2)} \right = 1.001 \pm 0.021$ |
| $F_0^{\bar{B}_s^0 \rightarrow D_s}(M_\pi^2)$ | — | 0.673 ± 0.011 | |
| $A_0^{\bar{B} \rightarrow D^*}(M_K^2)$ | — | 0.708 ± 0.038 | $\left \frac{A_0^{\bar{B}_s \rightarrow D_s^*}(M_\pi^2)}{A_0^{\bar{B} \rightarrow D^*}(M_K^2)} \right = 0.9729 \pm 0.080$ |
| $A_0^{\bar{B}_s^0 \rightarrow D_s^*}(M_\pi^2)$ | — | 0.689 ± 0.064 | |

Leading power

- Ratio of branching ratios to leading power

$$\mathcal{R}_{s/d}^P = \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_s^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ K^-)} = \frac{\tau_{B_s}}{\tau_{B_d}} \left| \frac{V_{ud}}{V_{us}} \right|^2 \frac{f_\pi^2}{f_K^2} \left| \frac{F_0^{\bar{B}_s \rightarrow D_s}(M_\pi^2)}{F_0^{\bar{B} \rightarrow D}(M_K^2)} \right|^2 \left| \frac{a_1(D_s^+ \pi^-)}{a_1(D^+ K^-)} \right|^2 \\ \times \left(\frac{M_{B_s}^2 - M_{D_s}^2}{M_B^2 - M_D^2} \right)^2 \frac{M_B^3}{M_{B_s}^3} \frac{\sqrt{\lambda(M_{B_s}^2, M_{D_s}^2, M_\pi^2)}}{\sqrt{\lambda(M_B^2, M_D^2, M_K^2)}}$$

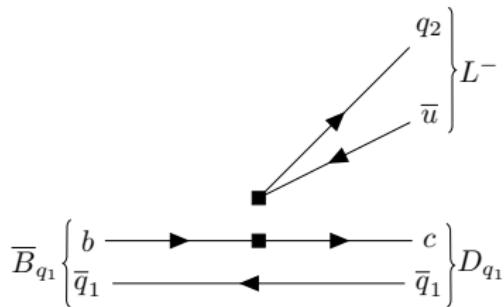
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- Numerical values at leading power

$$\mathcal{R}_{s/d}^P \Big|_{\text{LP}} = 13.5^{+0.6}_{-0.5}$$

$$\mathcal{R}_{s/d}^V \Big|_{\text{LP}} = 13.1^{+2.3}_{-2.0}$$

Subleading power



- Power corrections at $\mathcal{O}(\epsilon)$ arise from numerous effects
 - Higher twist effects to the light-meson LCDA
 - Hard-collinear gluon emission from the spectator quark q
 - Hard-collinear gluon emission from the heavy quarks b and c
 - Soft-gluon exchange between $B \rightarrow D$ and light-meson system
- Note: No explicit Λ/m_c power corrections if FFs in terms of QCD fields are used. Implicit corrections (from HQE in FFs) are part of error budget.

Subleading power

- Twist-three corrections to a pseudoscalar LCDA scale like

[Ball,Braun,Lenz'06]

$$\frac{M_{L-}^2}{E_L(m_u + m_{q_2})}$$

- Enhancement by light quark masses, can be numerically important
- But: Twist-three corrections to hadronic amplitude vanish at leading order in α_s
- Higher-twist corrections only enter at $\mathcal{O}(\alpha_s \epsilon^2)$ or higher

[Beneke'00]

Subleading power

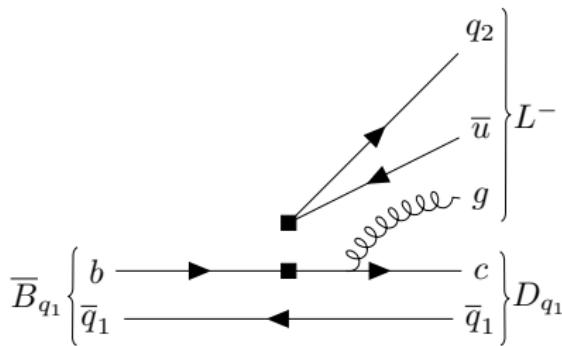
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- Enhancement by light quark masses, can be numerically important
 - But: Twist-three corrections to hadronic amplitude vanish at leading order in α_s
 - Higher-twist corrections only enter at $\mathcal{O}(\alpha_s \epsilon^2)$ or higher
- [Beneke'00]
- Hard-collinear gluon emission from the spectator quark q : Incompatible with a soft spectator quark inside both, the \bar{B}_q^0 and the D_q .

Subleading power



- Hard-collinear gluon emission from b and c
- $q\bar{q}g$ Fock state, contributes to three-particle LCDA of light meson
 - Twist-three contribution absent due to $V - A$ structure of weak current
 - First contribution at twist-four level, corresponding to $\mathcal{O}(\epsilon^2)$
 - Breaks $SU(3)_F$ symmetry maximally (vanishes for $L = \pi$, not for $L = K$)

Subleading power

- Estimating the twist-four, three-particle contribution

$$\langle 0 | \bar{q}(z) \gamma_\mu \gamma_5 g G_{\alpha\beta}(vz) s(-z) | K(P) \rangle =$$

$$= p_\mu (p_\alpha z_\beta - p_\beta z_\alpha) \frac{1}{pz} f_K \Phi_{4;K}(v, pz) + (p_\beta g_{\alpha\mu}^\perp - p_\alpha g_{\beta\mu}^\perp) f_K \Psi_{4;K}(v, pz) + \dots$$

- Integration measure

$$\mathcal{F}(v, pz) = \int \mathcal{D}\underline{\alpha} e^{-ipz(\alpha_2 - \alpha_1 + v\alpha_3)} \mathcal{F}(\underline{\alpha})$$

- Conformal expansion and numerical values of parameters

[Ball,Braun,Lenz'06]

$$\Phi_{4;K}(\underline{\alpha}) = 120\alpha_1\alpha_2\alpha_3[\phi_0^K + \phi_1^K(\alpha_1 - \alpha_2) + \phi_2^K(3\alpha_3 - 1) + \dots]$$

$$\Psi_{4;K}(\underline{\alpha}) = 30\alpha_3^2 \left\{ \theta_0^K(1 - \alpha_3) + \theta_1^K [\alpha_3(1 - \alpha_3) - 6\alpha_1\alpha_2] \right.$$

$$\left. + \theta_2^K [\alpha_3(1 - \alpha_3) - \frac{3}{2}(\alpha_1^2 + \alpha_2^2)] - (\alpha_1 - \alpha_2) \left[\psi_0^K + \alpha_3\psi_1^K + \frac{1}{2}(5\alpha_3 - 3)\psi_2^K \right] \right\}$$

Subleading power

- Estimating the twist-four, three-particle contribution

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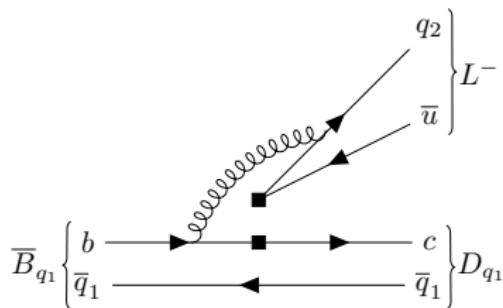
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$$\left. + \theta_2^K [\alpha_3(1 - \alpha_3) - \frac{3}{2}(\alpha_1^2 + \alpha_2^2)] - (\alpha_1 - \alpha_2) \left[\psi_0^K + \alpha_3\psi_1^K + \frac{1}{2}(5\alpha_3 - 3)\psi_2^K \right] \right\}$$

- Final numerical estimate

$$\frac{\mathcal{A}(\bar{B}^0 \rightarrow D^{(*)+} K^-) \Big|_{\text{NNLP(hc)}}}{\mathcal{A}(\bar{B}^0 \rightarrow D^{(*)+} K^-) \Big|_{\text{LP}}} \simeq \frac{C_1}{a_1} \times -0.64\%$$

Subleading power: Soft-gluon matrix element



- Consider matrix element $\langle D^{(*)+}(k) | \mathcal{O} | \bar{B}^0(q+k) \rangle$ of non-local operator

$$\begin{aligned}\mathcal{O} &\equiv -2 \int_0^{1/\Lambda_{\text{QCD}}} ds \bar{c}(0) \gamma^\mu (1 - \gamma_5) \tilde{G}_{\mu\nu}(-sn) n^\nu b(0) \\ &= -2i \int_0^\infty \frac{d\omega_2}{\omega_2} \times \bar{c}(0) \gamma^\mu (1 - \gamma_5) \delta [\omega_2 - (n \cdot iD)] \tilde{G}_{\mu\nu}(0) n^\nu b(0) \\ &\equiv -2i \int_0^\infty \frac{d\omega_2}{\omega_2} \tilde{\mathcal{O}}(\omega_2) \equiv -2i \tilde{\mathcal{O}}\end{aligned}$$

Subleading power: Soft-gluon and total

- Estimate matrix element $\langle D^{(*)+}(k) | \tilde{\mathcal{O}} | \bar{B}^0(q+k) \rangle$ with light-cone sum rules
 - Additional intermed. steps (quark-hadron duality, Borel transformation)
- Numerical estimate of non-local matrix elements

$$\langle D^+(k) | \mathcal{O} | \bar{B}^0(q+k) \rangle = i [0.13, 1.3] \text{ GeV}^2$$

$$\langle D^{*+}(k, \epsilon(\lambda=0)) | \mathcal{O} | \bar{B}^0(q+k) \rangle = i [0.078, 0.78] \text{ GeV}^2$$

- Upper bound: $\times 10$ increase of number obtained w/ nominal input values
- Normalizing to local matrix elements

$$\frac{\langle D^+(k) | \mathcal{O} | \bar{B}^0(q+k) \rangle}{i(m_B^2 - m_D^2) F_0^{\bar{B} \rightarrow D}(0)} = [0.76, 7.6]\%$$

$$\frac{\langle D^{*+}(k, \lambda=0) | \mathcal{O} | \bar{B}^0(q+k) \rangle}{i(m_B^2 - m_{D^*}^2) A_0^{\bar{B} \rightarrow D^*}(0)} = [0.46, 4.6]\%$$

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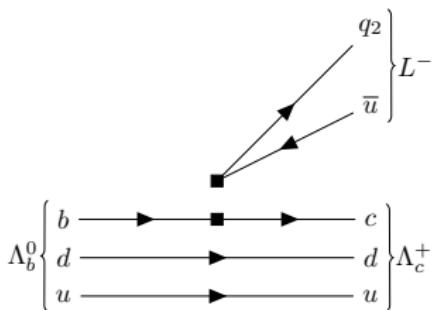
Total size of power corrections

$$\mathcal{R}_{s/d}^P \Big|_{\text{NLP}} / \mathcal{R}_{s/d}^P \Big|_{\text{LP}} - 1 \approx -1.7\%$$

$$\mathcal{R}_{s/d}^V \Big|_{\text{NLP}} / \mathcal{R}_{s/d}^V \Big|_{\text{LP}} - 1 \approx -1.7\%$$

Baryonic decays

[Bordone,Gubernari,Jung,van Dyk,TH w.i.p.]



- In baryonic decays pick $\Lambda_b \rightarrow \Lambda_c K^-$ as tree-dominated mode
 - no color-suppressed tree or penguins amplitudes
 - absence / smallness of annihilation to be confirmed
- Define the ratios

$$\mathcal{R}^{\frac{1}{2}^+/P} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ K^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ K^-)}$$

$$\mathcal{R}^{\frac{1}{2}^+/V} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ K^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} K^-)}$$

Baryonic decays

- At leading power, $\Lambda_b \rightarrow \Lambda_c K^-$ fulfills a QCD factorization formula similar to the mesonic case

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ K^-) = \tau_{\Lambda_b} \frac{G_F^2 |V_{cb} V_{us}^*|^2}{8\pi} f_K^2 \frac{[\lambda(m_{\Lambda_b}^2, m_{\Lambda_c}^2, m_K^2)]^{1/2}}{4m_{\Lambda_b}^3}$$
$$\times [(m_{\Lambda_b} - m_{\Lambda_c})^2 |a_1(D^+ K^-)|^2 |f_0(M_K^2)|^2 s_+ + (m_{\Lambda_b} + m_{\Lambda_c})^2 |a_1(D^{*+} K^-)|^2 |g_0(M_K^2)|^2 s_-]$$

- Formula consists of two terms due to non-trivial spin of the Λ_b
- Same expression for tree-amplitudes as in mesonic case appear
- Appearance of two $\Lambda_b \rightarrow \Lambda_c$ form factors

[Leibovich,Ligeti,Stewart,Wise'03; Feldmann,Yip'11; Detmold,Lehner,Meinel'15]

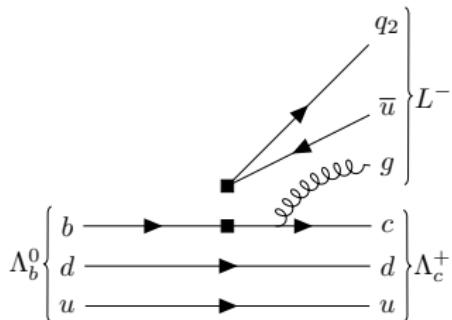
- Numerical values from lattice calculation

[Detmold,Lehner,Meinel'15]

$$|f_0(M_K^2)|^2 = 0.1810 \pm 0.0053$$

$$|g_0(M_K^2)|^2 = 0.1504 \pm 0.0045$$

$\Lambda_b \rightarrow \Lambda_c K^-$ at subleading power



- Many effects from mesonic case carry over to baryonic case.
Many arguments for their smallness as well
 - Higher twist effects
 - Only depend on the properties of the $K^- \Rightarrow$ are of $\mathcal{O}(\alpha_s \epsilon^2)$
 - Hard-collinear gluon emissions
 - Three-parton Fock state inside the K^- and $V - A$ structure of charged current forbids twist-3 contribution \Rightarrow are of $\mathcal{O}(\epsilon^2)$

$\Lambda_b \rightarrow \Lambda_c K^-$ at subleading power

- Only non-trivial piece is soft-gluon exchange

$$\langle \Lambda_c(k, s_{\Lambda_c}) | \tilde{O} | \Lambda_b(p, s_{\Lambda_b}) \rangle$$

- Estimate via light-cone sum rules not possible at present
 - Understanding of four-particle Λ_b LCDAs still incomplete
- Estimate this matrix element from dimensional arguments

$$\frac{\langle \Lambda_c(k, s_{\Lambda_c}) | \tilde{O} | \Lambda_b(p, s_{\Lambda_b}) \rangle}{\langle \Lambda_c(k, s_{\Lambda_c}) | \bar{c} i \not{q} b | \Lambda_b(p, s_{\Lambda_b}) \rangle} \sim \frac{\Lambda_{\text{had}}}{m_b} \simeq 10\%.$$

- Is $\sim 30\%$ larger than corresponding estimate for $\bar{B} \rightarrow D$ transitions
- Still, the ratios $\mathcal{R}^{\frac{1}{2}^+/P}$ and $\mathcal{R}^{\frac{1}{2}^+/V}$ are very clean probes of QCD fact.

Final numerical result (still preliminary)

$$\mathcal{R}^{\frac{1}{2}^+/P} = \frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} \left(0.761 \pm 0.033 \Big|_{\text{LP}} \pm 0.021 \Big|_{\text{NLP}, \Lambda_b} \right)$$

$$\mathcal{R}^{\frac{1}{2}^+/V} = \frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} \left(0.703 \pm 0.080 \Big|_{\text{LP}} \pm 0.019 \Big|_{\text{NLP}, \Lambda_b} \right)$$

Conclusion

- Determination of fragmentation fractions from hadronic decays represents a viable option
- Modes and ratios thereof that are very clean in QCDF are identified
- We provide a reliable and conservative estimate for the size of power corrections, although this remains challenging, especially in the baryonic case
- Λ_b fragmentation fraction f_{Λ_b} can be determined from hadronic decays by means of our results once data becomes available

[Numbers for f_s / f_d are presented in 2007.10338]

Backup slides

More details on soft-gluon matrix element

- Estimate matrix element $\langle D^{(*)+}(k) | \tilde{\mathcal{O}} | \bar{B}^0(q+k) \rangle$ with light-cone sum rules
- Define correlation functions with interpolating currents for D and D^*

$$\Pi_{D^{(*)}}(q, k) = i \int d^4x e^{ikx} \langle 0 | \mathcal{T} \left\{ J_{\text{int}}^{D^{(*)}}(x), \tilde{\mathcal{O}} \right\} | \bar{B}^0(q+k) \rangle$$

- Insert complete set of states to obtain hadronic representation, e.g. for D

$$\Pi_D^{\text{had}}(q, k) = \frac{f_D m_D^2}{m_c} \frac{\langle D^+ | \tilde{\mathcal{O}} | \bar{B}^0(q+k) \rangle}{m_D^2 - k^2} + \frac{1}{\pi} \int_{s_h}^{\infty} ds \frac{\tilde{\rho}_D(s, q^2)}{s - k^2}$$

with spectral density $\tilde{\rho}_D$ for excited and continuum states. Similar for D^*

- On the other hand, access correlator in a light-cone OPE

$$\begin{aligned} \Pi_{D^{(*)}}^{\text{OPE}}(q, k) &= \int d\omega_2 \int d^4x \int d^4p' e^{i(k-p') \cdot x} \left[\Gamma_{D^{(*)}} \frac{p' + m_c}{m_c^2 - p'^2} \gamma^\mu (1 - \gamma_5) \right]_{ab} \\ &\quad \times \langle 0 | \bar{d}^a(x) \delta[\omega_2 - in \cdot D] \tilde{G}_{\mu\nu}(0) n^\nu h_v^b(0) | \bar{B}^0 \rangle \end{aligned}$$

and match onto hadronic representation