Rare Semileptonic $b \to d\ell^+\ell^-$ Processes

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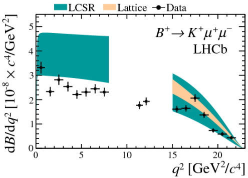
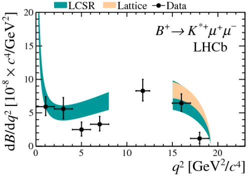
Outline

- $b \to d$ vs $b \to s$
- $B \to \pi \ell^+ \ell^-$ at large hadronic recoil
  - ▷ $B \to \pi$ form factors
  - ▷ Non-local hadronic effects
  - ▷ Observables
  - ▷ New physics effects
- $B_s^0 \to \bar{K}^0 \ell^+ \ell^-$ at large hadronic recoil
- Other $b \to d \ell^+ \ell^-$ modes

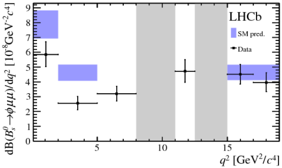
Anomalies in $b \to s\ell^+\ell^-$



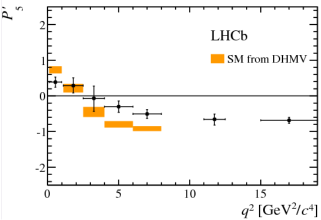
[LHCb, JHEP 1406 (2014) 133]



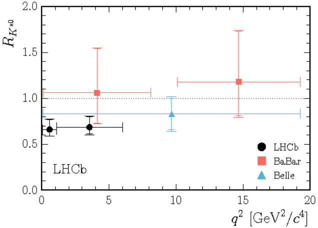
[LHCb, JHEP 1406 (2014) 133]



[LHCb, JHEP 1509 (2015) 179]



[LHCb, JHEP 1602 (2016) 104]

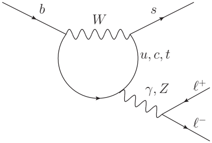


[LHCb, JHEP 1708 (2017) 055]

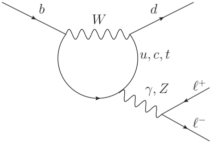
and other anomalies in

$b \to s\ell^+\ell^-$ transitions

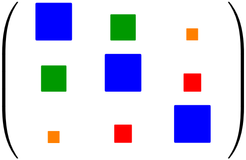
$b \to d$ vs $b \to s$



vs



$V_{\mathrm{CKM}} \sim$



- Additionally CKM suppressed

$$\left|\frac{V_{tb}V_{td}^*}{V_{tb}V_{ts}^*}\right| \approx 0.22 \quad \Rightarrow \quad \left|\frac{V_{tb}V_{td}^*}{V_{tb}V_{ts}^*}\right|^2 \approx 0.05$$

- $b \to d$ transitions induce non-vanishing direct CP-asymmetry
  - ▷ In $b \to s$:

$$|V_{tb}V_{ts}^*| \sim |V_{cb}V_{cs}^*| \ll |V_{ub}V_{us}^*|$$

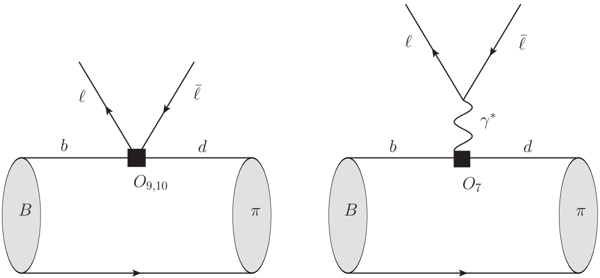
  - ▷ In $b \to d$:

$$|V_{tb}V_{td}^*| \sim |V_{cb}V_{cd}^*| \sim |V_{ub}V_{ud}^*|$$

- Also sensitive to contribution from NP

$B \to \pi \ell^+ \ell^-$ decays

- Have been measured by LHCb [JHEP 12 (2012) 125; JHEP 10 (2015) 034]
- $\mathcal{H}_{\rm eff}^{b\to d} \sim -\lambda_t \sum_{i=3}^{10} C_i\, \mathcal{O}_i + \lambda_u \sum_{i=1}^{2} C_i\, \mathcal{O}_i^u + \lambda_c \sum_{i=1}^{2} C_i\, \mathcal{O}_i^c \qquad \lambda_p = V_{pb} V_{pd}^*$



$\sim (C_9, C_{10}) f_{B\pi}^+(q^2)$ $\qquad$ $\sim C_7 f_{B\pi}^T(q^2)$

- $f_{B\pi}^+(q^2), f_{B\pi}^T(q^2)$ – form factors

Form factors from LCSR

- Form factors parametrise hadronic matrix element

$$\langle \pi(p)|\bar{d}\gamma^\mu b|B(p+q)\rangle \sim f^+_{B\pi}(q^2)$$

- Form factors are calculated from QCD Light Cone Sum Rule (LCSR)
- Starting object – correlation function

$$F^\mu_{B\pi}(p,q) = i\int d^4x\, e^{iqx}\langle \pi^+(p)|\,T\{\underbrace{\bar{u}(x)\gamma^\mu b(x)}_{\text{Quark current}},\ \underbrace{m_b\bar{b}(0)i\gamma_5 d(0)}_{\text{B-meson interpolating current}}\}|0\rangle$$

$$= F_{B\pi}(q^2,(p+q)^2)p^\mu + \tilde{F}_{B\pi}(q^2,(p+q)^2)q^\mu$$

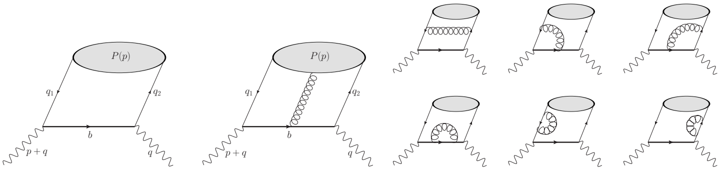
- Region of light-cone dominance ($x^2 \sim 0$): $q^2 \ll m_b^2, \quad (p+q)^2 \ll m_b^2$

$$\langle \pi^+(p)|\bar{u}(x)\gamma^\mu\gamma_5 d(0)|0\rangle|_{x^2\to 0} \sim \int du\, e^{iupx}\phi_\pi(u) + \ldots$$

$\phi_\pi(u)$ - pion light cone distribution amplitude (LCDA)

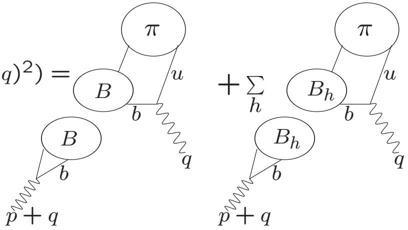
Form factors from LCSR

- OPE =



- Hadronic dispersion ⇒ relation

$F(q^2,(p+q)^2) =$



$\sim f_B f^+_{B\pi}(q^2)$ quark-hadron duality

Form factors from LCSR

- The current accuracy of OPE:

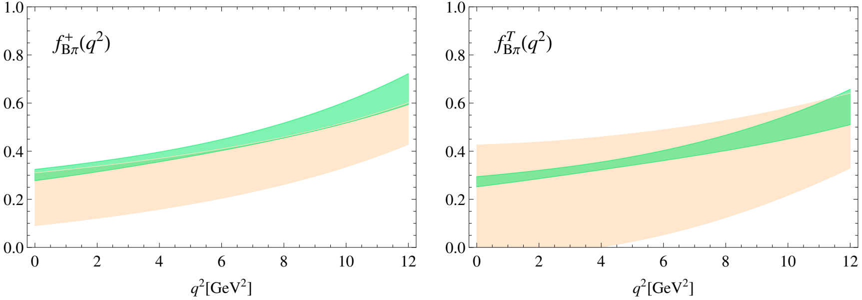
$$\text{OPE} = \left(T_0^{(2)} + (\alpha_s/\pi)T_1^{(2)} + (\alpha_s/\pi)^2 T_2^{(2)}\right) \otimes \varphi_\pi^{(2)}$$

$$+\left(T_0^{(3)} + (\alpha_s/\pi)T_1^{(3)}\right) \otimes \varphi_\pi^{(3)} + T_0^{(4)} \otimes \varphi_\pi^{(4)} + \langle \bar{q}q\rangle \left(T_0^{(5)} \otimes \varphi_\pi^{(2)} + T_0^{(6)} \otimes \varphi_\pi^{(3)}\right)$$

$T_n^{(k)}$ - hard-scattering kernels, $\phi_\pi^{(k)}$ - pion LCDAs ($k = 2, 3, \ldots$ - twist)

- LO twist 2, 3, 4
  [V.Belyaev, A.Khodjamirian, R.Rückl (1993); V.Braun, V.Belyaev, A.Khodjamirian, R.Rückl (1996)]
- NLO $O(\alpha_s)$ twist 2
  [A.Khodjamirian, R.Rückl, S.Weinzierl, O. Yakovlev (1997); E.Bagan, P.Ball, V.Braun (1997)]
- NLO $O(\alpha_s)$ twist 3
  [P. Ball, R. Zwicky (2001); G.Duplancic, A.Khodjamirian, B.Melic, Th.Mannel, N.Offen (2007)]
- Part of NNLO $O(\alpha_s^2\beta_0)$ twist 2 [A. Bharucha (2012)]
- LO twist 5 and twist 6 in factorization approximation [A.V. Rusov (2017)]

[A. Khodjamirian, A.V. Rusov (2017)]

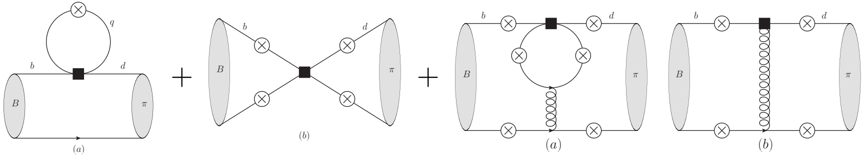


LCSR vs Lattice QCD (extrapolations from high q^2)

[FermiLab Lattice and MILC (2015)]

Nonlocal effects in $B \to \pi \ell^+ \ell^-$ decays

- Additional diagrams give rise to nonlocal hadronic amplitudes



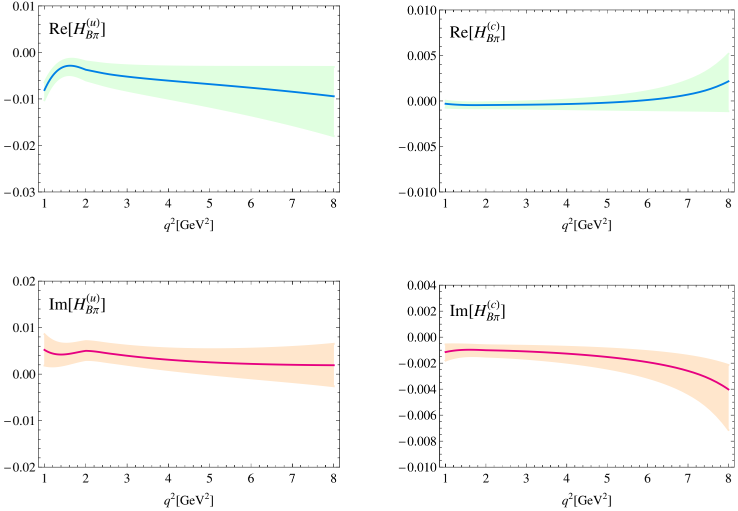
$$+ \ldots$$

- Their contributions are absorbed in q^2-dependent correction to Wilson coefficient C_9:

$$\Delta C_9(q^2) = \frac{16\pi^2}{f^+_{B\pi}(q^2)} \left(\frac{\lambda_u}{\lambda_t} \mathcal{H}^{(u)}_{B\pi}(q^2) + \frac{\lambda_c}{\lambda_t} \mathcal{H}^{(c)}_{B\pi}(q^2) \right)$$

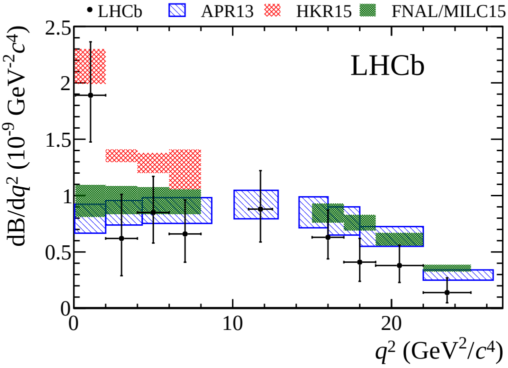
- $\mathcal{H}^{(c)}_{B\pi}(q^2), \mathcal{H}^{(u)}_{B\pi}(q^2)$ – nonlocal hadronic amplitudes

Results for $\mathcal{H}_{B\pi}^{(u)}, \mathcal{H}_{B\pi}^{(c)}$



Theory vs LHCb measurement

- Differential branching fraction in $B^\pm \to \pi^\pm \mu^+ \mu^-$ [LHCb, JHEP 10 (2015) 034]



■ - including non-local effects and resonances contributions
[Ch. Hambrock, A. Khodjamirian, A.V. Rusov (2015)]

Probing NP in $B^\pm \to \pi^\pm \mu^+ \mu^-$ decays

- Consider NP effective operators

$$\mathcal{O}_{9,L} = (\bar{d}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10,L} = (\bar{d}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_{9,R} = (\bar{d}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10,R} = (\bar{d}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- Preliminary results [A.V. Rusov, paper in preparation]

Scenario	1σ-interval
Only C_9^{NP}	$[-5.2, -2.0]$
Only C_{10}^{NP}	$[+1.6, +6.6]$
$C_9^{NP} = -C_{10}^{NP}$	$[-1.7, -0.8]$

$$C_9^{NP} = C_{9,L} + C_{9,R}$$

$$C_{10}^{NP} = C_{10,L} + C_{10,R}$$

- For comparison, from global fit of $b \to s\ell^+\ell^-$ observables (in one of the scenarios)

$$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.62$$ [B. Capdevila et al., JHEP 1801 (2018) 093]

$$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.63$$ [W. Altmannshofer et al., Phys.Rev. D96 (2017), 055008]

Direct CP asymmetry of $B \to \pi\ell^+\ell^-$ decays

- Definition of direct CP asymmetry

$$\mathcal{A}_{\rm CP}[q_1^2, q_2^2] = \frac{\mathrm{BR}(B^- \to \pi^-\ell^+\ell^-; q_1^2 \leq q^2 \leq q_2^2) - \mathrm{BR}(B^+ \to \pi^+\ell^+\ell^-; q_1^2 \leq q^2 \leq q_2^2)}{\mathrm{BR}(B^- \to \pi^-\ell^+\ell^-; q_1^2 \leq q^2 \leq q_2^2) + \mathrm{BR}(B^+ \to \pi^+\ell^+\ell^-; q_1^2 \leq q^2 \leq q_2^2)}$$

- Our prediction (only at low q^2 range)

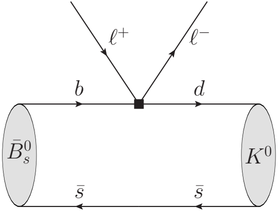
$$\mathcal{A}_{\rm CP}[1\,\mathrm{GeV}^2, 6\,\mathrm{GeV}^2] = -0.15 \pm 0.11$$

- LHCb measurement of total CP-asymmetry [LHCb, JHEP 10 (2015) 034]

$$\mathcal{A}_{\rm CP}[q^2_{\rm min}, q^2_{\rm max}] = -0.11 \pm 0.12 \pm 0.01$$

- Looking forward to data by LHCb on binned CP-asymmetry

$\bar{B}_s^0 \to K^0 \ell^+ \ell^-$ decays



[A. Khodjamirian, A.V. Rusov (2017)]

- New results for $B_s \to K$ form factors and corresponding nonlocal hadronic amplitudes
- CP-averaged q^2-binned branching fraction of $\bar{B}_s^0 \to K^0 \ell^+ \ell^-$

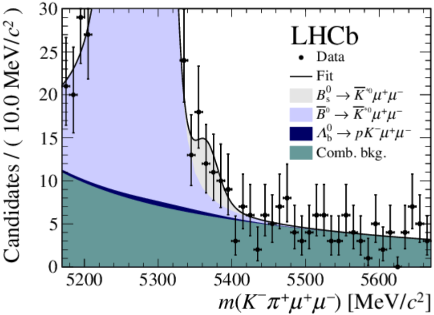
$$\mathcal{B}_{B_s K}[1.0\,\mathrm{GeV}^2,\ 6.0\,\mathrm{GeV}^2] = (4.38^{+0.62}_{-0.57} \pm 0.28) \times 10^{-8}\,\mathrm{GeV}^{-2}$$

- q^2-binned direct CP-asymmetry in $\bar{B}_s^0 \to K^0 \ell^+ \ell^-$ decays

$$\mathcal{A}_{\mathrm{CP}}[1.0\,\mathrm{GeV}^2,\ 6.0\,\mathrm{GeV}^2] = -0.04^{+0.01}_{-0.03}$$

- Data by LHCb anticipated

$B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay



First evidence of the $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ (with a significance of 3.4 standard deviations)
[LHCb, JHEP07 (2018) 020]

- A related theoretical analysis (incl. non-local effects + resonances) in progress [A. Lenz, M. Piscopo, A.V. Rusov]

Conclusion

- $b \to d\ell^+\ell^-$ processes are potential sources of New Physics
- CKM suppressed vs $b \to s$ $\Rightarrow$ more statistics needed
- More interesting observables (incl. non-vanishing CP-asymmetry)
- Not discussed:
  - ▷ $B^0 \to \pi^+\pi^-\mu^+\mu^-$
  - ▷ $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$
- Looking forward to (more) data on
  - ▷ $B^\pm \to \pi^\pm\mu^+\mu^-$ (incl. diff. CP-asymmetry)
  - ▷ $\bar{B}_s^0 \to K^{*0}\mu^+\mu^-$
  - ▷ $\bar{B}_s^0 \to K^0\mu^+\mu^-$
  - ▷ $B \to \rho\mu^+\mu^-$

Backup

Effective Hamiltonian

Effective Hamiltonian for $b \to q$ [Buchalla, Buras, Lautenbacher (1996)]

$$\mathcal{H}_{\rm eff}^{b\to q} = \frac{4G_F}{\sqrt{2}} \left(\lambda_u^{(q)} \sum_{i=1}^{2} C_i\, \mathcal{O}_i^u + \lambda_c^{(q)} \sum_{i=1}^{2} C_i\, \mathcal{O}_i^c - \lambda_t^{(q)} \sum_{i=3}^{10} C_i\, \mathcal{O}_i \right) + h.c.$$

$$\lambda_p^{(q)} = V_{pb} V_{pq}^*, \quad p = u, c, t, \quad q = d, s$$

- $B \to K\ell^+\ell^-$: $\lambda_t^{(s)} \approx -\lambda_c^{(s)} \sim \lambda^2 \gg \lambda_u^{(s)} \sim \lambda^4$
- $B \to \pi\ell^+\ell^-$: $\lambda_t^{(d)} \sim \lambda_c^{(d)} \sim \lambda_u^{(d)} \sim \lambda^3$
- $B_s \to K\ell^+\ell^-$: $\lambda_t^{(d)} \sim \lambda_c^{(d)} \sim \lambda_u^{(d)} \sim \lambda^3$

Operators basis

$$\mathcal{O}_9 = \frac{\alpha_{\rm em}}{4\pi}\left(\bar{d}_L\gamma^\mu b_L\right)\left(\bar{\ell}\gamma_\mu\ell\right), \quad \mathcal{O}_{10} = \frac{\alpha_{\rm em}}{4\pi}\left(\bar{d}_L\gamma^\mu b_L\right)\left(\bar{\ell}\gamma_\mu\gamma_5\ell\right),$$

$$\mathcal{O}_{7\gamma} = -\frac{e\, m_b}{16\pi^2}\left(\bar{d}_L\sigma^{\mu\nu}b_R\right)F_{\mu\nu},$$

$$\mathcal{O}_1^u = \left(\bar{d}_L\gamma_\mu u_L\right)\left(\bar{u}_L\gamma^\mu b_L\right), \quad \mathcal{O}_2^u = \left(\bar{d}_L^i\gamma_\mu u_L^j\right)\left(\bar{u}_L^j\gamma^\mu b_L^i\right),$$

$$\mathcal{O}_1^c = \left(\bar{d}_L\gamma_\mu c_L\right)\left(\bar{c}_L\gamma^\mu b_L\right), \quad \mathcal{O}_2^c = \left(\bar{d}_L^i\gamma_\mu c_L^j\right)\left(\bar{c}_L^j\gamma^\mu b_L^i\right),$$

$$\mathcal{O}_3 = \left(\bar{d}_L\gamma_\mu b_L\right)\sum_q\left(\bar{q}_L\gamma^\mu q_L\right), \quad \mathcal{O}_4 = \left(\bar{d}_L^i\gamma_\mu b_L^j\right)\sum_q\left(\bar{q}_L^j\gamma^\mu q_L^i\right),$$

$$\mathcal{O}_5 = \left(\bar{d}_L\gamma_\mu b_L\right)\sum_q\left(\bar{q}_R\gamma^\mu q_R\right), \quad \mathcal{O}_6 = \left(\bar{d}_L^i\gamma_\mu b_L^j\right)\sum_q\left(\bar{q}_R^j\gamma^\mu q_R^i\right),$$

$$\mathcal{O}_{8g} = -\frac{g_s m_b}{16\pi^2}\left(\bar{d}_L^i\sigma_{\mu\nu}(T^a)^{ij}b_R^j\right)G^{a\,\mu\nu}$$

Hadronic input

Form Factors

$$\langle \pi(p)|\bar{q}\gamma^\mu b|B(p+q)\rangle = f^+_{B\pi}(q^2)\,(2p^\mu + q^\mu) + \left(f^+_{B\pi}(q^2) - f^0_{B\pi}(q^2)\right)\frac{m_B^2 - m_\pi^2}{q^2}q^\mu$$

$$\langle \pi(p)|\bar{q}\sigma^{\mu\nu}q_\nu b|B(p+q)\rangle = \frac{i f^T_{B\pi}(q^2)}{m_B + m_\pi}\left[2q^2 p^\mu + \left(q^2 - \left(m_B^2 - m_\pi^2\right)\right)q^\mu\right]$$

Nonlocal effects via correlation functions

$$\mathcal{H}^{(p)}_{B\pi,\,\mu} = i\int d^4x\, e^{iqx}\langle \pi(p)|\mathrm{T}\Big\{j^{\mathrm{em}}_\mu(x), \Big[C_1\mathcal{O}^p_1(0) + C_2\mathcal{O}^p_2(0)$$

$$+\sum_{k=3-6,8g} C_k\mathcal{O}_k(0)\Big]\Big\}|B(p+q)\rangle = \left[(p\cdot q)q_\mu - q^2 p_\mu\right]\mathcal{H}^{(p)}_{B\pi}(q^2)$$

Amplitude

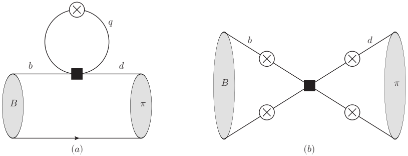
$$A(B \to \pi\ell^+\ell^-) = \frac{G_F}{\sqrt{2}}\frac{\alpha_{\rm em}}{\pi}\lambda_t f^+_{B\pi}(q^2)\Bigg[\left(\bar\ell\gamma^\mu\ell\right) p_\mu \left(C_9 + \frac{2m_b}{m_B+m_P}C_7^{\rm eff}\frac{f^T_{B\pi}(q^2)}{f^+_{B\pi}(q^2)}\right)$$

$$+\left(\bar\ell\gamma^\mu\gamma_5\ell\right) p_\mu C_{10} - (\bar\ell\gamma^\mu\ell)p_\mu \underbrace{\frac{16\pi^2}{f^+_{B\pi}(q^2)}\left(\frac{\lambda_u}{\lambda_t}\mathcal{H}^{(u)}_{B\pi}(q^2) + \frac{\lambda_c}{\lambda_t}\mathcal{H}^{(c)}_{B\pi}(q^2)\right)}_{\Delta C_9(q^2)}\Bigg]$$

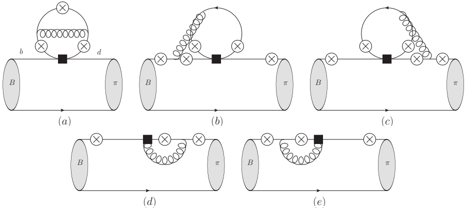
- Wilson coefficients at **NLO**
- Form factors from **LCSR** [A. Khodjamirian, A.V. Rusov (2017)]
- Nonlocal hadronic amplitudes via **QCDF, LCSR** and **hadronic dispersion relations** [Ch. Hambrock, A. Khodjamirian, A.V. Rusov (2015)]

Calculation of $\mathcal{H}_{B\pi}^{(u,c)}(q^2)$ at $q^2 < 0$

- LO, factorizable loop and weak annihilation
  [M. Beneke, Th. Feldmann, D. Seidel (2001)]

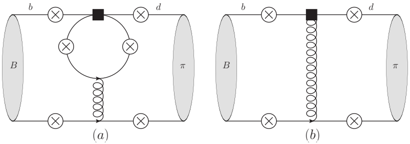


- NLO, factorizable
  [H.H.Asatryan, H.M. Asatrian, C. Greub, M. Walker (2002);
  H.M.Asatrian, K. Bieri, C. Greub, M. Walker (2004)]

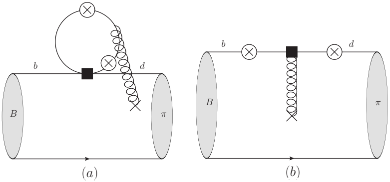


Calculation of $\mathcal{H}_{B\pi}^{(u,c)}(q^2)$ at $q^2 < 0$

- NLO, nonfactorizable (hard gluons)
  [M. Beneke, Th. Feldmann, D. Seidel (2001)]



- Soft gluons, nonfactorizable
  [A. Khodjamirian, Th. Mannel, A.A. Pivovarov, Y.-M. Wang (2010)]
  [A. Khodjamirian, Th. Mannel, Y.-M. Wang (2013)]



Dispersion relations for $\mathcal{H}_{BP}^{(u,c)}(q^2)$

Dispersion relations:

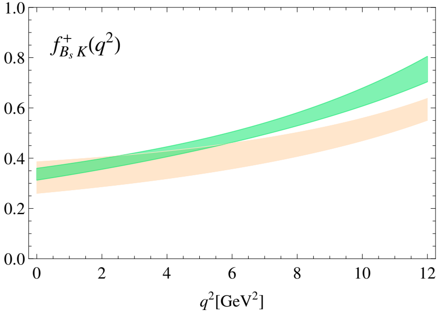
$$\mathcal{H}_{BP}^{(u,c)}(q^2) = (q^2 - q_0^2)\left[\sum_{V=\rho,\omega,J/\psi,\psi(2S)} \frac{k_V f_V A_{BVP}^{u,c}}{(m_V^2 - q_0^2)(m_V^2 - q^2 - i m_V \Gamma_V^{\rm tot})}\right.$$

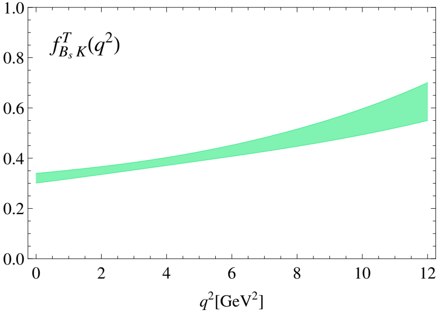
$$\left. + \int_{s_0^{u,c}}^{\infty} ds \frac{\rho_{BP}^{(u,c)}(s)}{(s - q_0^2)(s - q^2 - i\epsilon)}\right] + \mathcal{H}_{BP}^{(u,c)}(q_0^2)$$

- $A_{BVP}^{u,c} = |A_{BVP}^{u,c}| e^{i\delta_{BVP}^{u,c}}$
- $|A_{BVP}^{u,c}|$ are extracted from nonleptonic $B \to VP$ decays
- $\delta_{BVP}^{u,c}$ are extracted from the fit of the dispersion relation to $\mathcal{H}_{BP}^{(u,c)}(q^2)$ for $q^2 < 0$
- For $\rho_{BP}^{(u,c)}(s)$ one applies quark-hadron duality

Results for the $B_s \to K$ form factors

A. Khodjamirian, A.V. Rusov, 1703.04765 [hep-ph]





Lattice QCD results: C.M. Bouchard et al., hep-lat: 1406.2279

Results for $\mathcal{H}^{(u)}_{B_s K}, \mathcal{H}^{(c)}_{B_s K}$