Probing New Physics in $b \to d$ Transitions

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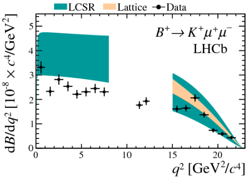
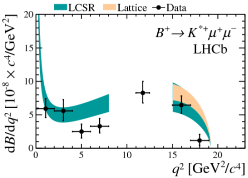
based on ArXiv: 1911.12819 (published in JHEP)

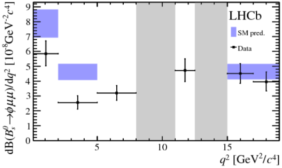
Anomalies in $b \to s\ell^+\ell^-$



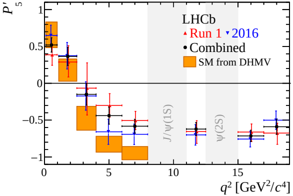
[ArXiv:1403.8044]



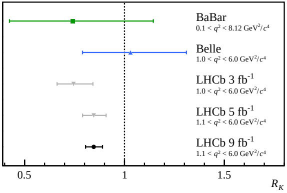
[ArXiv:1403.8044]



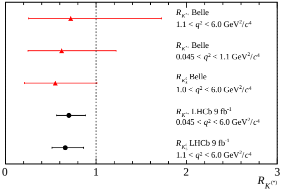
[ArXiv:2105.14007]



[ArXiv: 2003.04831]

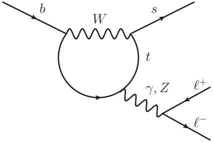


[ArXiv:2103.11769]

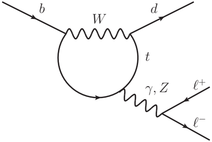


[ArXiv:2110.09501]

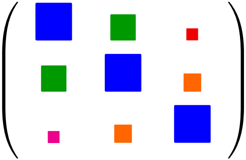
$b \to d$ vs $b \to s$



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 $b \to s$:

$$|V_{tb}V_{ts}^*| \sim |V_{cb}V_{cs}^*| \sim \lambda^2 \gg |V_{ub}V_{us}^*| \sim \lambda^4$$

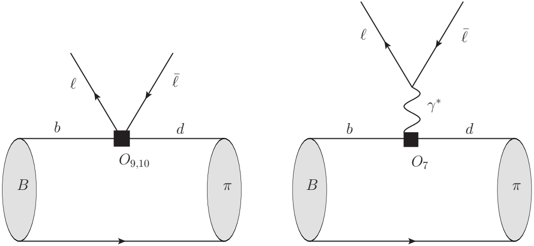
  - ▷ In $b \to d$:

$$|V_{tb}V_{td}^*| \sim |V_{cb}V_{cd}^*| \sim |V_{ub}V_{ud}^*| \sim \lambda^3$$

- Also sensitive to contribution from New Physics (NP)

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

- Have been measured by the LHCb collaboration
  [JHEP 12 (2012) 125; JHEP 10 (2015) 034]



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

$$\lambda_p = V_{pb} V_{pd}^* \qquad p = u, c, t$$

Hadronic input

Form Factors

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

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

Nonlocal effects via correlation functions

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

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

The amplitude

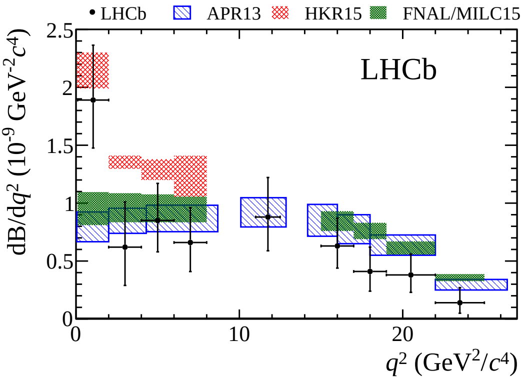
$$A(B \to \pi \ell^+ \ell^-) = \frac{G_F}{\sqrt{2}} \frac{\alpha_{\rm em}}{\pi} \lambda_t f^+_{B\pi}(q^2) \Bigg[(\bar{\ell}\gamma^\mu \ell)\, p_\mu \left(C_9 + \frac{2 m_b}{m_B + m_P} C_7^{\rm eff} \frac{f^T_{B\pi}(q^2)}{f^+_{B\pi}(q^2)} \right)$$

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

- Wilson coefficients C_i at **NLO**
- Form factors $f^{+,T}_{B\pi}(q^2)$ from **LCSR** [A. Khodjamirian, A.V. Rusov (2017)]
- Nonlocal hadronic amplitudes $\mathcal{H}^{(u,c)}_{BP}(q^2)$ via **QCDF, LCSR** and **hadronic dispersion relations** [Ch. Hambrock, A. Khodjamirian, A.V. Rusov (2015)]

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 [Hambrock, Khodjamirian, AR (2015)]

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

- Consider NP effective operators

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

- The estimates [A.V. Rusov (2019)]

Scenario	1σ-interval
$C_9^{\rm NP}$ only	$[-5.2, -1.9]$
$C_{10}^{\rm NP}$ only	$[+1.4, +6.8]$
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	$[-1.8, -0.7] \cup [-7.0, -5.8]$

$$C_9^{NP} = C_{9,L} + C_{9,R}$$
$$C_{10}^{NP} = C_{10,L} + C_{10,R}$$

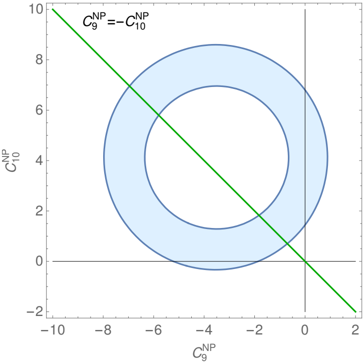
- For example, from global fit of the $b \to s\ell^+\ell^-$ observables

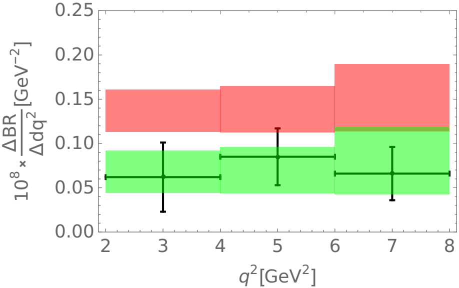
$$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.46 \pm 0.10$$ [M. Alguero et al. (2019)]

$$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.41 \pm 0.10$$ [A. Arbey et al. (2019)]

$$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.53 \pm 0.08$$ [J. Aebischer et al. (2019)]

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





Impact on the $B^0 \to \mu^+\mu^-$ decays

- The current experimental bounds

$$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} \quad 95\%\,\mathrm{CL} \quad \text{[ATLAS (2019)]}$$
$$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10} \quad 95\%\,\mathrm{CL} \quad \text{[CMS (2019)]}$$
$$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \quad 95\%\,\mathrm{CL} \quad \text{[LHCb (2021)]}$$

- The Standard Model prediction [M. Beneke, C. Bobeth, R. Szafron (2019)]

$$\mathrm{BR}^{\mathrm{SM}}(B^0 \to \mu^+\mu^-) = (1.027 \pm 0.051) \times 10^{-10}$$

- The NP estimates

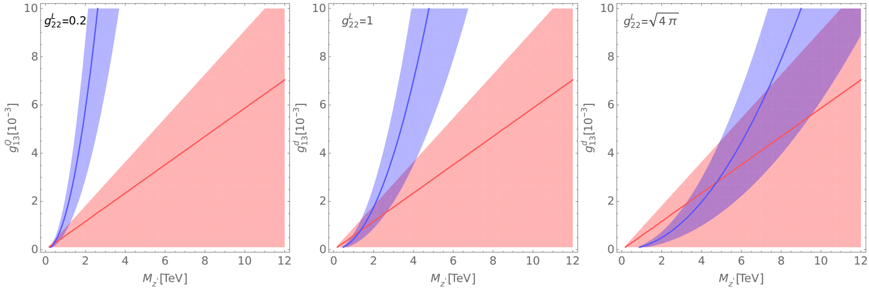
$$\mathrm{BR}^{\mathrm{NP}}(B^0 \to \mu^+\mu^-) \simeq (0.6 \pm 0.2) \times 10^{-10} \quad \text{if } C_{10}^{\mathrm{NP}} = C_{10,L}$$
$$\mathrm{BR}^{\mathrm{NP}}(B^0 \to \mu^+\mu^-) \simeq (1.8 \pm 0.4) \times 10^{-10} \quad \text{if } C_{10}^{\mathrm{NP}} = C_{10,R}$$

- Not yet possible to resolve the left- and right-handed quark operators

Impact on $B^0 - \bar{B}^0$-mixing

- Consider as an example the NP model with Z' boson

$$\mathcal{L}_{Z'}^{\text{eff}} = -\frac{1}{2M_{Z'}{}^2}\left[\left(g_{13}^{Q}\right)^2(\bar{d}_L\gamma^\mu b_L)(\bar{d}_L\gamma_\mu b_L) + 2\,g_{13}^{Q}\,g_{22}^{L}\,(\bar{d}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu \mu_L)\right] + \ldots$$



The LFU in $b \to d\ell^+\ell^-$

- The LFU ratio: $R_\pi[q^2_{\rm min}, q^2_{\rm max}] = \dfrac{{\rm Br}(B \to \pi\mu^+\mu^-)[q^2_{\rm min}, q^2_{\rm max}]}{{\rm Br}(B \to \pi e^+e^-)[q^2_{\rm min}, q^2_{\rm max}]}$
- In the SM: $R_\pi^{\rm SM} \approxeq 1$
- [Bordone et al., arXiv:2101.11626]:
  - ▷ considering NP effects

$$R_\pi = R_\pi^{\rm SM} + b_v\,\Delta C_9 + (b_v - b_L)\,\Delta C_{10}$$

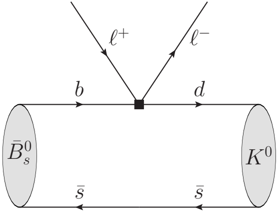
  - ▷ using $\Delta C_9 = -\Delta C_{10} = -0.43 \pm 0.11$ from $b \to s$ fit

[J. Fuentes-Martin et al, arXiv:1909.02519]

$$R_\pi[1.1, 8.0]\Big|^{\rm NP}_{U(2)^5} = 0.79 \pm 0.05_{\rm NP} \pm 0.02_{\rm LD}$$

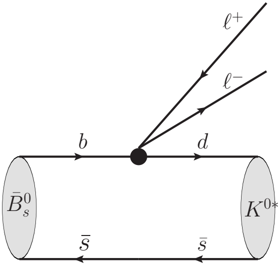
- Measurement of $B^\pm \to \pi^\pm e^+e^-$?

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



- Similar to $B \to \pi \ell^+ \ell^-$ up to $SU(3)_F$-breaking
- [A. Khodjamirian, A.V. Rusov (2017)]:
  - ▷ New results for the $B_s \to K$ form factors and corresponding nonlocal hadronic amplitudes
  - ▷ Predictions for the differential branching fraction and CP-asymmetry at large hadronic recoil
- No measurement so far

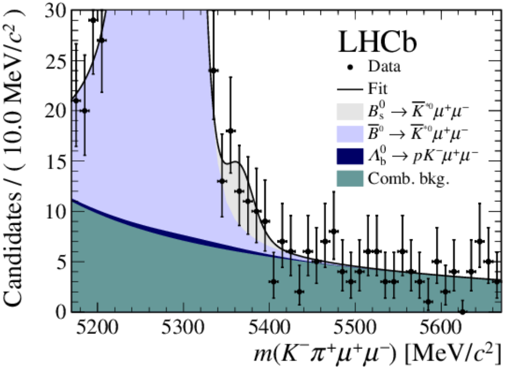
The $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay



- Vector final state K^{0*}-meson ($J^P = 1^-$)
  $\to$ 3 helicity amplitudes
- 7 form factors
  6 nonlocal hadronic amplitudes
  $\to$ more involved theoretical analysis
- $\mathrm{BR}(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) \sim 10^{-8}$

- Richer set of interesting observables
  - ▷ Differential decay rate
  - ▷ Nonzero direct CP-asymmetry
  - ▷ Angular distributions (incl. P_5')

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



First evidence of the $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay (with a significance of 3.4σ)

[LHCb, JHEP 07 (2018) 020]

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 data on
  - ▷ $B^\pm \to \pi^\pm\mu^+\mu^-$ (incl. diff. CP-asymmetry)
  - ▷ $\bar{B}_s^0 \to K^{0(*)}\mu^+\mu^-$
  - ▷ $B^0 \to \mu^+\mu^-$

Backup

Operators basis

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

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

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

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

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

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

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

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

- The current accuracy of OPE:

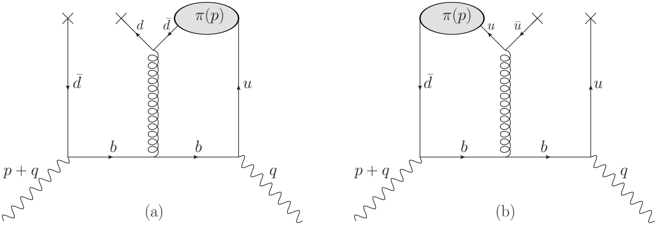
$$\text{OPE} = \left(T_0^{(2)} + (\alpha_s/\pi)\,T_1^{(2)} + (\alpha_s/\pi)^2\,T_2^{(2)}\right) \otimes \varphi_\pi^{(2)}$$

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

$T_n^{(k)}$ - 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)]

Factorizable twist-5 and twist-6 contributions



- In the framework of the factorization approximation

$$[F_{B\pi}(q^2)]_{\rm tw5,6} \sim \langle \bar{q} q \rangle \left(T_0^{(5)} \otimes \varphi_P^{(2)} + T_0^{(6)} \otimes \varphi_P^{(3)} \right)$$

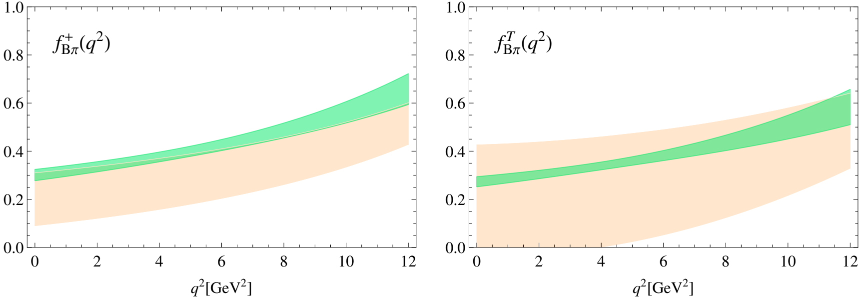
- Calculation reveals [A.V. Rusov (2017)]

$$[f^+_{B\pi}(0)]_{\rm tw5,6} / f^+_{B\pi}(0) < 0.1\%$$

- $\Rightarrow$ Truncation up to twist-4 contributions is reliable

Results for $B \to \pi$ form factors

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

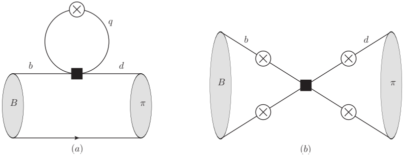


LCSR vs Lattice QCD (extrapolations from high q^2)

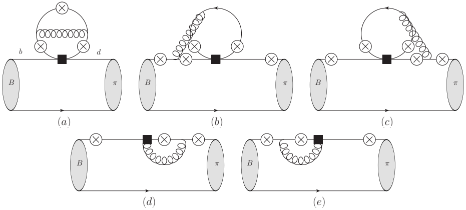
[FermiLab Lattice and MILC (2015)]

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)]

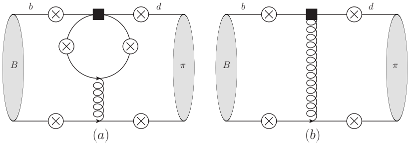


- NLO, factorizable [H.H.Asatryan, H.M. Asatrian, C. Greub, M. Walker (2002)] [H.M.Asatrian, K. Bieri, C. Greub, M. Walker (2004)]

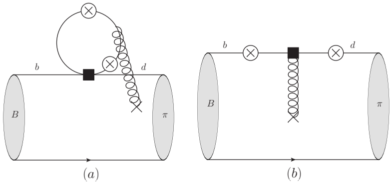


Calculation of $\mathcal{H}^{(u,c)}_{B\pi}(q^2)$ at $q^2 < 0$

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



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



▷ Need to be updated using new determination of B-meson LCDAs [see talk by Danny van Dyk]

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

- The dispersion relations:

$$\mathcal{H}_{BP}^{(u,c)}(q^2) = (q^2 - q_0^2)\left[\sum_{V=\rho,\omega,J/\psi,\psi(2S)} \frac{k_V f_V A_{BVP}^{u,c}}{(m_V^2 - q_0^2)(m_V^2 - q^2 - i m_V \Gamma_V^{\rm tot})} + \int\limits_{s_0^{u,c}}^{\infty} ds \frac{\rho_{BP}^{(u,c)}(s)}{(s - q_0^2)(s - q^2 - i\epsilon)}\right] + \mathcal{H}_{BP}^{(u,c)}(q_0^2)$$

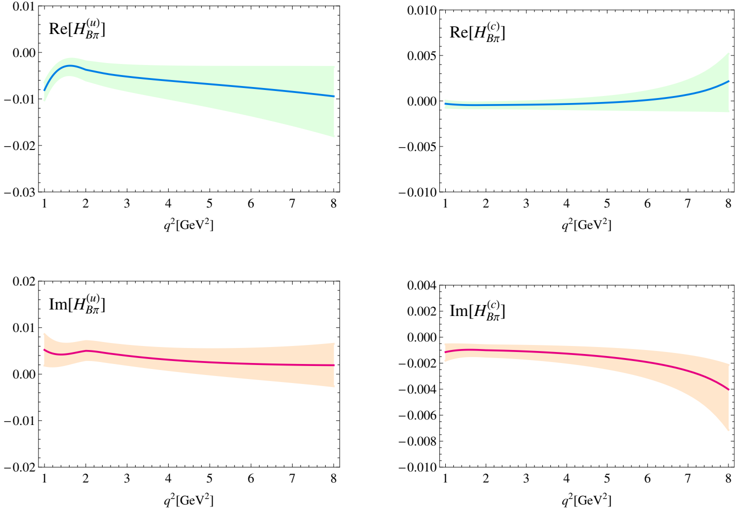
▷ $A_{BVP}^{u,c} = |A_{BVP}^{u,c}| e^{i\delta_{BVP}^{u,c}}$

▷ $|A_{BVP}^{u,c}|$ are extracted from nonleptonic $B \to VP$ decays

▷ $\delta_{BVP}^{u,c}$ are extracted from the fit of the DR to $\mathcal{H}_{BP}^{(u,c)}(q^2)$ at $q^2 < 0$

▷ For $\rho_{BP}^{(u,c)}(s)$ one applies quark-hadron duality

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



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

- Definition of direct CP asymmetry

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

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

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

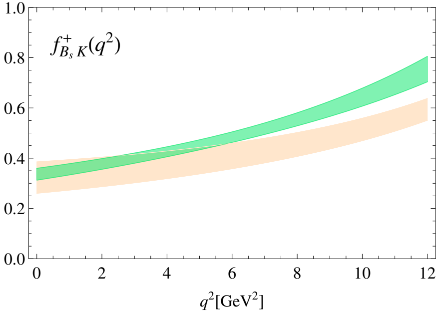
- SM prediction (only at low q^2 range) [A. Khodjamirian, A.V. Rusov (2017)]

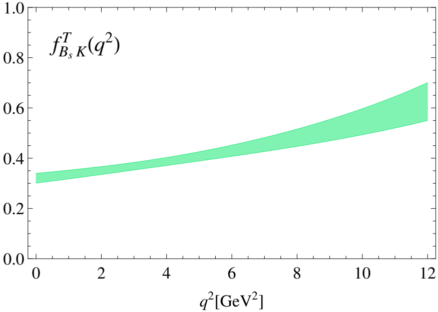
$$\mathcal{A}_{\rm CP}[1\,{\rm GeV}^2, 6\,{\rm GeV}^2] = -0.15 \pm 0.11$$

- The measurement of the binned CP-asymmetry is anticipated

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