

Theoretical analysis of rare decay $B^+ \rightarrow \pi^+\tau^+\tau^-$

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Outline

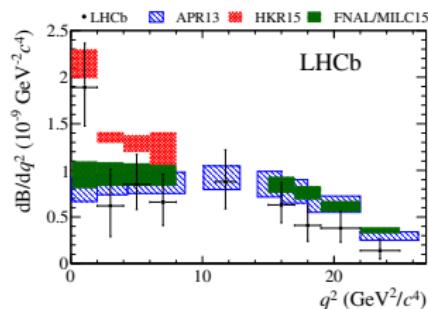
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Rare Decays Induced by $b \rightarrow s$ and $b \rightarrow d$ FCNCs

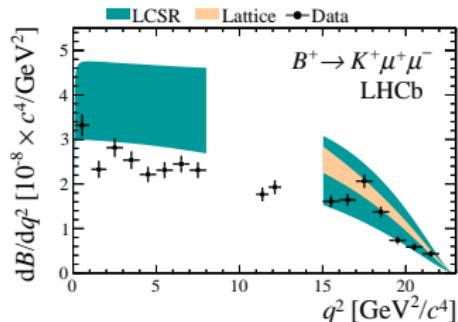
- Rare semileptonic decays of B -mesons and Λ_b -baryons due to $b \rightarrow s$ and $b \rightarrow d$ transitions, where b , s , and d are quarks with $Q = -1/3$, may be sensitive to “New Physics”
- At present, the proton-proton collider LHC and B -factory SuperKEKB are the only sources of experimental data on these decays
- Branching fractions of semileptonic B -meson decays due to $b \rightarrow s$ transition, like $B^\pm \rightarrow K^{(*)\pm} \mu^+ \mu^-$, $B^0 \rightarrow K^{(*)0} \mu^+ \mu^-$, $B_s^0 \rightarrow \phi \mu^+ \mu^-$, lepton-pair invariant mass distributions in them, and coefficients in angular distributions are experimentally measured quite precisely
- As for exclusive decays originated by the $b \rightarrow d$ neutral current, similar $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay only was observed by the LHCb Collab. in 2012 and analyzed in details in 2015

$\mu^- \mu^+$ -distributions in semileptonic B -meson decays

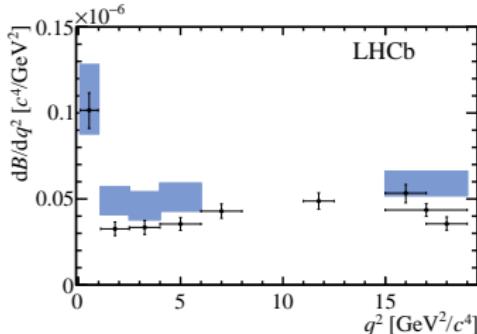
$B^+ \rightarrow \pi^+ \mu^- \mu^+$ [JHEP 10 (2015) 034]



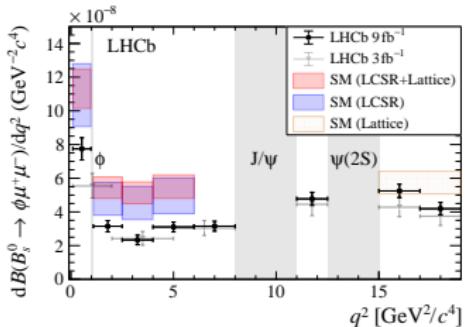
$B^+ \rightarrow K^+ \mu^- \mu^+$ [JHEP 06 (2014) 133]



$B^0 \rightarrow K^{*0} \mu^- \mu^+$ [JHEP 11 (2016) 047]



$B_s^0 \rightarrow \phi \mu^- \mu^+$ [PRL 127 (2021) 151801]



Effective Electroweak Lagrangian for $b \rightarrow s(d)$ FCNCs

- Theoretically, calculations are convenient to do within the Effective Electroweak Hamiltonian approach
- Lagrangian density includes all the other quark flavors
 $q = u, d, s, c, b$

$$\mathcal{L}_{\text{eff}}(x) = \mathcal{L}_{\text{QED}}(x) + \mathcal{L}_{\text{QCD}}(x) - \mathcal{H}_{\text{weak}}^{b \rightarrow d}(x) - \mathcal{H}_{\text{weak}}^{b \rightarrow s}(x)$$

- Flavor-changing neutral current (FCNC) term $\mathcal{H}_{\text{weak}}^{b \rightarrow d}$ describes $b \rightarrow d$ transition

$$\mathcal{H}_{\text{weak}}^{b \rightarrow d} = -\frac{4G_F}{\sqrt{2}} \sum_{p=u,c} V_{pd}^* V_{pb} \sum_j C_j(\mu) \mathcal{P}_j(\mu) + \text{h. c.}$$

- G_F — Fermi constant
 $V_{q_1 q_2}$ — CKM matrix element
 $C_j(\mu)$ — Wilson coefficients
 $\mathcal{P}_j(\mu)$ — four-fermion operators for $b \rightarrow d$ transition

Operator Basis

- For most phenomenological applications, only operators $\mathcal{P}_j(\mu)$ of the dimension $d = 6$ are relevant
- Basis of local operators for the $b \rightarrow d$ transition

- Tree operators ($p = u, c$)

$$\mathcal{P}_1^{(p)} = (\bar{d}\gamma_\mu LT^a p)(\bar{p}\gamma^\mu LT^a b) \quad \mathcal{P}_2^{(p)} = (\bar{d}\gamma_\mu Lp)(\bar{p}\gamma^\mu Lb)$$

- Penguin operators

$$\mathcal{P}_3 = (\bar{d}\gamma_\mu Lb) \sum_q (\bar{q}\gamma^\mu q) \quad \mathcal{P}_4 = (\bar{d}\gamma_\mu LT^a b) \sum_q (\bar{q}\gamma_\mu T^a q)$$

$$\mathcal{P}_5 = (\bar{d}\gamma_\mu \gamma_\nu \gamma_\rho Lb) \sum_q (\bar{q}\gamma_\mu \gamma_\nu \gamma_\rho q)$$

$$\mathcal{P}_6 = (\bar{d}\gamma_\mu \gamma_\nu \gamma_\rho LT^a b) \sum_q (\bar{q}\gamma_\mu \gamma_\nu \gamma_\rho T^a q)$$

- Electromagnetic and chromomagnetic dipole operators

$$\mathcal{P}_{7\gamma} = \frac{e}{16\pi^2} [\bar{d}\sigma^{\mu\nu}(m_b R + m_d L)b] F_{\mu\nu}$$

$$\mathcal{P}_{8g} = \frac{g_{st}}{16\pi^2} [\bar{d}\sigma^{\mu\nu}(m_b R + m_d L)T^a b] G_{\mu\nu}^a$$

- Semileptonic operators

$$\mathcal{P}_{9\ell(10\ell)} = \frac{\alpha}{2\pi} (\bar{d}\gamma_\mu Lb) \sum_\ell (\bar{\ell}\gamma^\mu(\gamma^5)\ell)$$

Matrix elements of $B \rightarrow P$ transition

$$\langle P(k) | \bar{p} \gamma^\mu b | B(p_B) \rangle = f_+(q^2) \left[p_B^\mu + k^\mu - \frac{m_B^2 - m_P^2}{q^2} q^\mu \right] + f_0(q^2) \frac{m_B^2 - m_P^2}{q^2} q^\mu$$

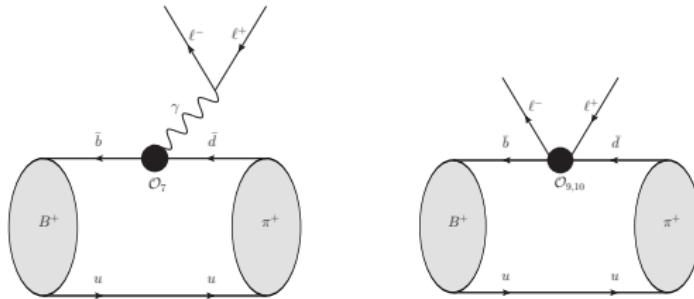
$$\langle P(k) | \bar{p} \gamma^\mu \gamma_5 b | B(p_B) \rangle = 0$$

$$\langle P(k) | \bar{p} \sigma^{\mu\nu} q_\nu b | B(p_B) \rangle = i \left[(p_B^\mu + k^\mu) q^2 - q^\mu (m_B^2 - m_P^2) \right] \frac{f_T(q^2)}{m_B + m_P}$$

$$\langle P(k) | \bar{p} \sigma^{\mu\nu} \gamma_5 q_\nu b | B(p_B) \rangle = 0$$

- $q^\mu = p_B^\mu - k^\mu$ is the momentum transferred to leptons
- $f_+(q^2)$, $f_0(q^2)$, $f_T(q^2)$ are the transition form factors

$B^+ \rightarrow \pi^+ \ell^+ \ell^-$ decay



Operators \mathcal{P}_7 , \mathcal{P}_9 , and \mathcal{P}_{10} give tree-level contributions to the decay amplitude ($N = \frac{G_F}{\sqrt{2}} V_{tb} V_{td}^* \frac{e^2}{g_{st}^2}$)

$$\mathcal{M}_9 = N C_9 \langle \pi(P_\pi) | \bar{d}_L \gamma^\mu b_L | B(P_B) \rangle [\bar{U}(q_1) \gamma_\mu U(-q_2)]$$

$$\mathcal{M}_{10} = N C_{10} \langle \pi(P_\pi) | \bar{d}_L \gamma^\mu b_L | B(P_B) \rangle [\bar{U}(q_1) \gamma_\mu \gamma_5 U(-q_2)]$$

$$\mathcal{M}_7 = -i N \frac{2m_b}{q^2} C_7 \langle \pi(P_\pi) | \bar{d}_L \sigma^{\mu\nu} q_\nu b_R | B(P_B) \rangle [\bar{U}(q_1) \gamma_\mu U(-q_2)]$$

$B \rightarrow P\ell^+\ell^-$ differential branching fraction

Depends on the dilepton invariant-mass q^2

$$\frac{d\text{Br}(B \rightarrow P\ell^+\ell^-)}{dq^2} = S_P \frac{2G_F^2 \alpha^2 \tau_B}{3(4\pi)^5 m_B^3} |V_{tb} V_{tp}^*|^2 \beta_\ell \lambda^{3/2}(q^2) F^{BP}(q^2),$$

$$F^{BP}(q^2) = F_{97}^{BP}(q^2) + F_{10}^{BP}(q^2)$$

$$F_{97}^{BP}(q^2) = \left(1 + \frac{2m_\ell^2}{q^2}\right) \left| C_9^{\text{eff}}(q^2) f_+^{BP}(q^2) + \right.$$

$$\left. + \frac{2m_b}{m_B + m_P} C_7^{\text{eff}}(q^2) f_T^{BP}(q^2) + \textcolor{red}{L}_A^{BP}(q^2) + \textcolor{blue}{\Delta C}_V^{BP}(q^2) \right|^2$$

$$F_{10}^{BP}(q^2) = \left(1 - \frac{4m_\ell^2}{q^2}\right) \left| C_{10}^{\text{eff}} f_+^{BP}(q^2) \right|^2 + \frac{6m_\ell^2}{q^2} \frac{(m_B^2 - m_P^2)^2}{\lambda(q^2)} \left| C_{10}^{\text{eff}} f_0^{BP}(q^2) \right|^2$$

S_P is the final-meson flavor factor ($S_{\pi^\pm} = 1$ and $S_{\pi^0} = 1/2$)

$p = s, d$ is flavor in $b \rightarrow p$ transition

$$\beta_\ell = \sqrt{1 - 4m_\ell^2/q^2}, \quad \lambda(q^2) = (m_B^2 + m_P^2 - q^2)^2 - 4m_B^2 m_P^2$$

Long-distance contributions (LDC)

- Contributions from $B \rightarrow V(\rightarrow \ell^+ \ell^-)\pi$ decays, where $V = \rho^0, \omega, J/\psi, \psi(2S)$ are neutral mesons
- LDC for $B \rightarrow \pi \ell^+ \ell^-$ can be expressed as follows
[Hambrock et al., PRD 92 (2015) 074020]

$$\Delta C_V^{B\pi}(q^2) = -16\pi^2 \frac{V_{ub} V_{ud}^* H^{(u)}(q^2) + V_{cb} V_{cd}^* H^{(c)}(q^2)}{V_{tb} V_{td}^*}$$
$$H^{(p)}(q^2) = (q^2 - q_0^2) \sum_V \frac{k_V f_V A_{BV\pi}^p}{(m_V^2 - q_0^2)(m_V^2 - q^2 - im_V \Gamma_V^{\text{tot}})}$$

- k_V is valence quark content factor, f_V is the decay constant, $A_{BV\pi}^p$ ($p = u, c$) are transition amplitudes, Γ_V^{tot} is the total width of vector meson, $q_0^2 = -1.0 \text{ GeV}^2$
- Since the spectrum of $B^+ \rightarrow \pi^+ \tau^+ \tau^-$ in the region $q^2 \in [4m_\tau^2, (m_B - m_\pi)^2]$, there are only $\psi(2S)$ and higher resonances

Form Factor parameterizations

- Boyd-Grinstein-Lebed (BGL) parameterization ($i = +, 0, T$)

$$f_i(q^2) = \frac{1}{P_i(q^2)\phi_i(q^2, q_0^2)} \sum_{k=0}^N a_k^{(i)} [z(q^2, q_0^2)]^k,$$

$$z(q^2, q_0^2) = \frac{\sqrt{m_+^2 - q^2} - \sqrt{m_+^2 - q_0^2}}{\sqrt{m_+^2 - q^2} + \sqrt{m_+^2 - q_0^2}},$$

$$m_+ = m_B + m_\pi, \quad q_0^2 = 0.65(m_B - m_\pi)^2$$

- Blaschke factor: $P_{i=+,T}(q^2) = z(q^2, m_{B^*}^2)$ and $P_0(q^2) = 1$
- $\phi_i(q^2, q_0^2)$ is outer function depending on isospin factor and three parameters K_i , α_i , and β_i
- FFs $f_{+,T}(q^2)$ have poles at the mass squared of vector B^* -meson while $f_0(q^2)$ is free from poles
- Bourrely-Caprini-Lellouch (BCL) parameterization
- Modified Bourrely-Caprini-Lellouch (mBCL) parameterization

Form Factor parametrizations

- Boyd-Grinstein-Lebed (BGL) parameterization
- Bourrely-Caprini-Lellouch (BCL) parameterization ($i = +, T$)

$$f_i(q^2) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{N-1} b_k^{(i)} \left([z(q^2, q_0^2)]^k - (-1)^{k-N} \frac{k}{N} [z(q^2, q_0^2)]^N \right)$$

$$f_0(q^2) = \sum_{k=0}^{N-1} b_k^{(0)} z(q^2, q_0^2)^k$$

$$m_+ = m_B + m_\pi, \quad q_0^2 = m_+ (\sqrt{m_B} - \sqrt{m_\pi})^2$$

Form factors are considered as truncated series at $N = 4$

- Modified Bourrely-Caprini-Lellouch (mBCL) parameterization

Form Factor parametrizations

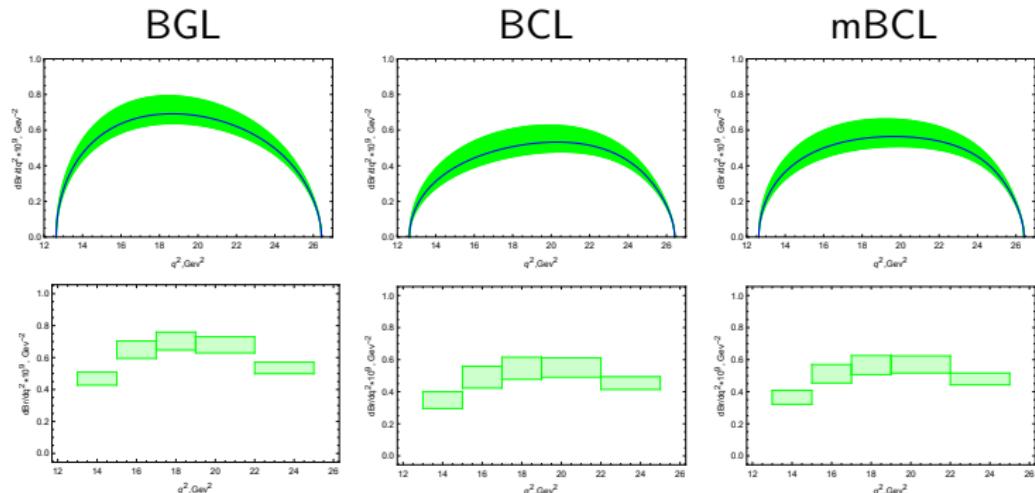
- Boyd-Grinstein-Lebed (BGL) parameterization
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($i = +, T$)

$$f_i(q^2) = \frac{f_i(q^2 = 0)}{1 - q^2/m_{B^*}^2} \left[1 + \sum_{k=1}^{N-1} b_k^{(i)} \left(\bar{z}_k(q^2, q_0^2) - (-1)^{k-N} \frac{k}{N} \bar{z}_N(q^2, q_0^2) \right) \right]$$

$$f_0(q^2) = \frac{f_+(q^2 = 0)}{1 - q^2/m_{B_0}^2} \left[1 + \sum_{k=1}^N b_k^{(0)} \bar{z}_k(q^2, q_0^2) \right]$$

- $\bar{z}_n(q^2, q_0^2) = z^n(q^2, q_0^2) - z^n(0, q_0^2)$
- q_0^2 is chosen as optimal value
- FF $f_0(q^2)$ has also the pole but at scalar B_0 -meson mass squared

Dilepton invariant-mass distribution for $B^+ \rightarrow \pi^+ \tau^+ \tau^-$ decay

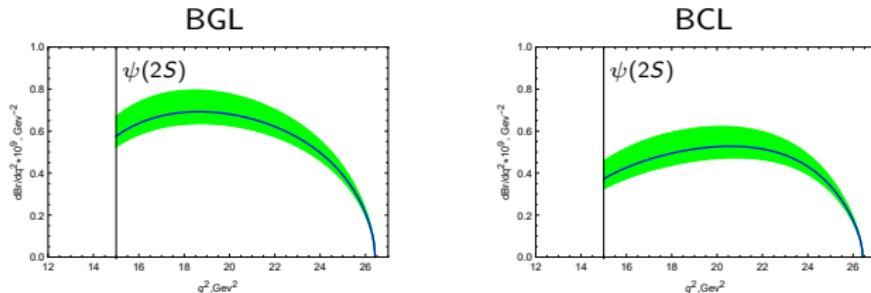


Total branching fraction for $B^+ \rightarrow \pi^+ \tau^+ \tau^-$ decay

	BGL	BCL	mBCL	Faustov, Galkin EPJC 74 2911 (2014)	Wang, Xiao PRD 86 114025 (2012)
$\text{Br}_{\text{th}} \times 10^9$	$7.56^{+1.04}_{-0.75}$	$6.00^{+0.81}_{-0.49}$	$6.28^{+0.88}_{-0.78}$	7.00 ± 0.70	$6.00^{+2.60}_{-2.10}$

Dilepton invariant-mass distribution for $B^+ \rightarrow \pi^+ \tau^+ \tau^-$ decay with LDC

- Taking into account $B \rightarrow \psi(2S)(\rightarrow \tau^+ \tau^-) \pi$ resonance

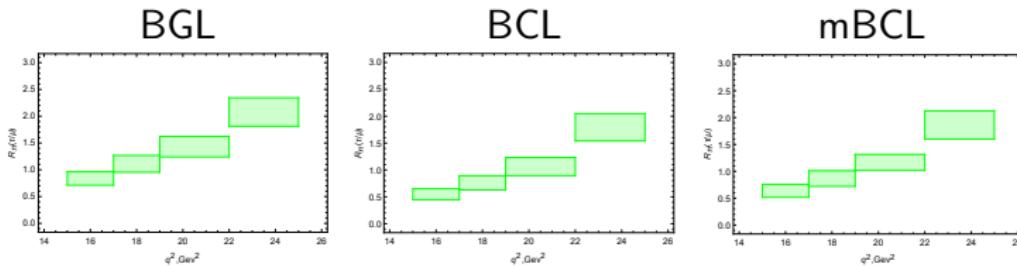


Branching fraction dependence on choice of amplitude phases (BCL)

$\delta_{\psi(2S)}^{(u)}$	$\delta_{\psi(2S)}^{(c)}$	$\text{Br}(B^+ \rightarrow \pi^+ \tau^+ \tau^-) \times 10^{-9}$
SDC		$6.00^{+0.81}_{-0.49}$
0	0	$5.79^{+0.78}_{-0.48}$
0	π	$6.23^{+0.84}_{-0.50}$
0	$3\pi/4$	$6.05^{+0.80}_{-0.47}$
$\pi/2$	π	$6.24^{+0.84}_{-0.51}$
$3\pi/2$	0	$5.78^{+0.78}_{-0.48}$

Theoretical predictions for the ratio $R_\pi^{(\tau/\mu)}$

$$R_\pi^{(\tau/\mu)}(q_1^2, q_2^2) = \frac{\int_{q_1^2}^{q_2^2} d\text{Br}(B^+ \rightarrow \pi^+ \tau^+ \tau^-)/dq^2}{\int_{q_1^2}^{q_2^2} d\text{Br}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/dq^2}$$



Theoretical predictions for the partial ratio $R_\pi^{(\tau/\mu)}$

$[q_1^2, q_2^2]$ (GeV^2)	$R_\pi^{(\tau/\mu)}$		
	BGL	BCL	mBCL
[15.0, 17.0]	0.84 ± 0.13	0.55 ± 0.10	0.64 ± 0.12
[17.0, 19.0]	1.11 ± 0.16	0.76 ± 0.13	0.86 ± 0.15
[19.0, 22.0]	1.43 ± 0.19	1.06 ± 0.17	1.17 ± 0.18
[22.0, 25.0]	2.08 ± 0.27	1.79 ± 0.25	1.86 ± 0.26

Summary and outlook

- A theoretical prediction for the total branching fraction of $B^+ \rightarrow \pi^+ \tau^+ \tau^-$ decay is obtained for various types of form factor parameterization
- Impact of Long-Distance contribution from $\psi(2S)$ -resonance is investigated, and the main result for BCL parameterization on the total branching fraction $\mathcal{B}_{\text{th}}(B^+ \rightarrow \pi^+ \tau^+ \tau^-) = (6.05^{+0.80}_{-0.47}) \times 10^{-9}$ is obtained
- For the semitauonic $B^+ \rightarrow \pi^+ \tau^+ \tau^-$ decay, theoretical predictions give a factor 2-3 suppression in comparison with $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ and it is an attractive process for experimental searches
- Detection of decays, containing tauons as final decay products, with sufficient accuracy is planned by the Belle collaboration on the scale of integrated luminosity $\sim 5 \text{ ab}^{-1}$

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<https://rscf.ru/project/22-22-00877/>)

Backup Slides

Wilson Coefficients

- At the matching scale μ_W , Wilson coefficients can be calculated as a perturbative expansion

$$C_j(\mu_W) = \sum_{k=0}^{\infty} \left[\frac{\alpha_s(\mu_W)}{4\pi} \right]^k C_j^{(k)}(\mu_W)$$

- Mixed under the operator renormalization
- Evolved to the b -quark scale by RGE
- Hierarchy in the Wilson coefficients exists; in the naive dimensional regularization scheme at the next-to-leading logarithmic (NLL) order

$C_1(m_b)$	-0.146	$C_3(m_b)$	0.011	$C_7(m_b)$	4.9×10^{-4}
$C_2(m_b)$	1.056	$C_4(m_b)$	-0.033	$C_8(m_b)$	4.6×10^{-4}
$C_{7\gamma}(m_b)$	-0.317	$C_5(m_b)$	0.010	$C_9(m_b)$	-9.8×10^{-3}
$C_{8g}(m_b)$	0.149	$C_6(m_b)$	-0.039	$C_{10}(m_b)$	1.9×10^{-3}

Effective Wilson Coefficients

- Branching fractions of B -meson decays induced by $b \rightarrow s(d) \ell^- \ell^+$ transitions are expressed through C_7^{eff} , C_9^{eff} , and C_{10}^{eff}
- In NNLO, effective Wilson coefficients are given as
[Asatrian et al. PRD 69 (2004) 074007]

$$C_7^{\text{eff}} = \left[1 + \frac{\alpha_s}{\pi} \omega_7(\hat{s}) \right] A_7 - \frac{\alpha_s}{4\pi} \left[C_1^{(0)} F_{1,c}^{(7)} + C_2^{(0)} F_{2,c}^{(7)} + \sum_{k=3}^6 C_k^{(0)} F_k^{(7)} + A_8^{(0)} F_8^{(7)} \right] - \\ - \frac{\alpha_s}{4\pi} \xi^{(q)} \left\{ C_1^{(0)} [F_{1,c}^{(7)} - F_{1,u}^{(7)}] + C_2^{(0)} [F_{2,c}^{(7)} - F_{2,u}^{(7)}] \right\}$$

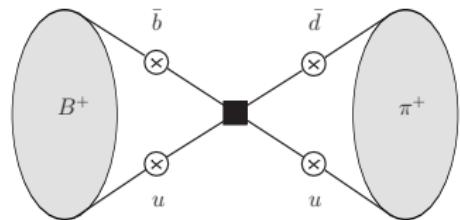
$$C_9^{\text{eff}} = \left[1 + \frac{\alpha_s}{\pi} \omega_9(\hat{s}) \right] \left\{ A_9 + T_9 h(\hat{m}_c^2, \hat{s}) + U_9 h(1, \hat{s}) + W_9 h(0, \hat{s}) + \xi^{(s)} T_{9a} \times \right. \\ \times \left. [h(\hat{m}_c^2, \hat{s}) - h(0, \hat{s})] \right\} - \frac{\alpha_s}{4\pi} \left[C_1^{(0)} F_{1,c}^{(9)} + C_2^{(0)} F_{2,c}^{(9)} + \sum_{k=3}^6 C_k^{(0)} F_k^{(9)} + A_8^{(0)} F_8^{(9)} \right] - \\ - \frac{\alpha_s}{4\pi} \xi^{(q)} \left\{ C_1^{(0)} [F_{1,c}^{(9)} - F_{1,u}^{(9)}] + C_2^{(0)} [F_{2,c}^{(9)} - F_{2,u}^{(9)}] \right\}$$

$$C_{10}^{\text{eff}} = \left[1 + \frac{\alpha_s}{\pi} \omega_{10}(\hat{s}) \right] A_{10}$$

- $\hat{m}_c = m_c/m_b$; $\xi^{(q)} = V_{ub} V_{uq}^*/(V_{tb} V_{tq}^*)$ ($q = d, s$)
- $\hat{s} = q^2/m_b^2$ is scaled lepton-pair momentum squared

Weak annihilation contribution in $B^+ \rightarrow \pi^+ \ell^+ \ell^-$ decay

Can be calculated within the LEET [Beneke et al. Eur.Phys.J.C41 173-188 (2005)]



$$L_A^{B\pi(t)}(q^2) = Q_q \frac{\pi^2}{3} \frac{4f_B f_\pi}{m_b} \lambda_{B,-}^{-1}(q^2) C_{34}$$

$$L_A^{B\pi(u)}(q^2) = -Q_q \frac{\pi^2}{3} \frac{4f_B f_\pi}{m_b} \lambda_{B,-}^{-1}(q^2) C_{12}$$

- Q_q is relative charge of spectator quark
- f_B and f_π are B - and π -meson decay constants
- $C_{34} = C_3 + \frac{4}{3}(C_4 + 12C_5 + 16C_6)$; $C_{12} = 3C_2$ are combinations of Wilson coefficients
- First inverse moment of B -meson LCDA enters these contributions (Grozin-Neubert model is used)

$$\lambda_{B,-}^{-1}(q^2) = \frac{e^{-q^2/(m_B \omega_0)}}{\omega_0} [i\pi - Ei(q^2/(m_B \omega_0))]$$

- Here, $Ei(z) = \int_z^{-\infty} dt e^t/t$ is the Exponential integral

Forecast on improving detector sensitivity on Belle II

[Snowmass Whitepaper: The Belle II Detector Upgrade Program]

Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$ V_{ub} $ (Exclusive)	4.5%	2%	1%	< 1%
$S_{CP}(B \rightarrow \eta' K_S^0)$	0.08	0.03	0.015	0.007
$A_{CP}(B \rightarrow \pi^0 K_S^0)$	0.15	0.07	0.025	0.018
$S_{CP}(B \rightarrow K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \rightarrow K^*\ell^+\ell^-)^\dagger$	0.26	0.09	0.03	0.01
$R(B \rightarrow D^*\tau\nu)$	0.018	0.009	0.0045	<0.003
$R(B \rightarrow D\tau\nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \rightarrow \tau\nu)$	24%	9%	4%	2%
$B(B \rightarrow K^*\nu\bar{\nu})$	—	25%	9%	4%
$\mathcal{B}(\tau \rightarrow \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \rightarrow \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

- The integrated luminosity $\sim 5 \text{ ab}^{-1}$ is planned to be achieved by 2026
- Further improving up to 50 ab^{-1} is expected after 2030