Rare decay modes

$b \to d\,\gamma$ and $b \to d\,\ell^+\ell^-$

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Outline

- Introduction, comparison of $b \to d$ with $b \to s$ transitions
- Inclusive $b \to d\,\gamma$ and $b \to d\,\ell^+\ell^-$ decays
- Exclusive $b \to d\,\gamma$ and $b \to d\,\ell^+\ell^-$ decays
- Conclusion

Note: This talk initialises our investigations on $b \to d$ transitions.
Comments and suggestions from theory and experiment are welcome!

Introduction, effective Hamiltonian

- Effective Hamiltonian for B decays, $q = s,\, d$

$$H_{\rm eff}(b \to q\gamma) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \left[\sum_{i=1}^{8} C_i(\mu) \cdot O_i(\mu) + \epsilon_q \sum_{i=1}^{2} C_i(\mu) \cdot (O_i(\mu) - O_i^u(\mu)) \right]$$

- $\epsilon_q = (V_{ub} V_{uq}^*)/(V_{tb} V_{tq}^*)$

- Operators involve

$$O_1 = (\bar{q}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad O_2 = (\bar{q}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$O_1^u = (\bar{q}_L \gamma_\mu T^a u_L)(\bar{u}_L \gamma^\mu T^a b_L) \qquad O_2^u = (\bar{q}_L \gamma_\mu u_L)(\bar{u}_L \gamma^\mu b_L)$$

$$O_7 = \frac{e}{16\pi^2} m_b(\mu)(\bar{q}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \qquad O_8 = \frac{g_s}{16\pi^2} m_b(\mu)(\bar{q}_L T^a \sigma_{\mu\nu} b_R) G^{a\mu\nu}$$

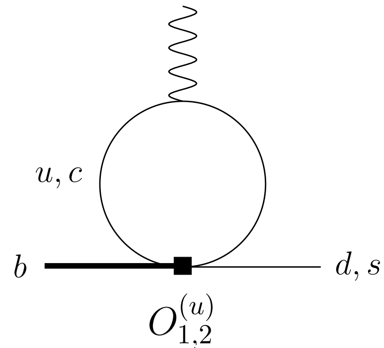
- Decisive difference between $b \to s$ and $b \to d$ transitions:

$$\epsilon_s = (V_{ub} V_{us}^*)/(V_{tb} V_{ts}^*) = -\lambda^2(\bar{\rho} - i\bar{\eta}) \simeq -0.01 + 0.02\, i$$

$$\epsilon_d = (V_{ub} V_{ud}^*)/(V_{tb} V_{td}^*) = \frac{\bar{\rho} - i\bar{\eta}}{1 - \bar{\rho} - i\bar{\eta}} \simeq -0.02 + 0.42\, i \ (!)$$

Introduction, $b \to s$ vs. $b \to d$ transitions

- CP asymmetries are therefore tiny in $b \to s$, but sizable in $b \to d$ transitions
- Up-quark loops play an important role in $b \to d$ transitions since ϵ_d is not small
- QCD corrections to the up-loop matrix elements are known at two loops
  [Asatrian,Bieri,Greub,Walker'03; Seidel'04]



- Non-factorizable power corrections of the form $1/m_q^2$ [Buchalla,Isidori,Rey'97]
  - $1/m_c^2$ corrections known and well under control
  - $1/m_u^2$ corrections naively blow up, but turn out to be of order $\mathcal{O}(\Lambda_{\text{QCD}}/m_b)$

Current exptl. world averages

- Branching ratios

Observable	WA in 10^{-6}
$B^+ \to K^{*+}\gamma$	42.1 ± 1.8
$B^0 \to K^{*0}\gamma$	43.5 ± 1.5
$B^+ \to \rho^+\gamma$	$0.98^{+0.25}_{-0.24}$
$B^0 \to \rho^0\gamma$	$0.86^{+0.15}_{-0.14}$
$B^0 \to \omega\gamma$	$0.44^{+0.18}_{-0.16}$
$s\gamma$	$352 \pm 23 \pm 9$
$d\gamma$	7.2 ± 3.5
$\rho\gamma$	$1.39^{+0.22}_{-0.21}$
$\rho/\omega\gamma$	$1.30^{+0.18}_{-0.19}$
$s\ell^+\ell^-$	$3.66^{+0.76}_{-0.77}\,, \quad \sqrt{q^2} > 0.2$ GeV
$K\ell^+\ell^-$	0.45 ± 0.04
$K^*\ell^+\ell^-$	$1.08^{+0.12}_{-0.11}$
$\pi\ell^+\ell^-$	< 0.062

- CP asymmetries

Observable	WA
$K^*\gamma$	-0.003 ± 0.017
$s\gamma$	-0.012 ± 0.028
$(s+d)\gamma$	-0.11 ± 0.12
$s\ell\ell$	-0.22 ± 0.26
$K^*e^+e^-$	-0.18 ± 0.15
$K^*\mu^+\mu^-$	-0.03 ± 0.13
$K^*\ell\ell$	-0.07 ± 0.08

Branching ratios of $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_d\gamma$

- For $E_\gamma > 1.6$ GeV one obtains in the SM [Hurth,Lunghi,Porod'03]

$$\mathcal{B}[\bar{B} \to X_d\gamma] = \left[1.38 \; {}^{+0.14}_{-0.21}\Big|_{\frac{m_c}{m_b}} \pm 0.15_{\rm CKM} \pm 0.09_{\rm param.} \pm 0.05_{\rm scale}\right] \times 10^{-5}$$

$$\frac{\mathcal{B}[\bar{B} \to X_d\gamma]}{\mathcal{B}[\bar{B} \to X_s\gamma]} = \left[3.82 \; {}^{+0.11}_{-0.18}\Big|_{\frac{m_c}{m_b}} \pm 0.42_{\rm CKM} \pm 0.08_{\rm param.} \pm 0.15_{\rm scale}\right] \times 10^{-2}$$

- Errors on $\frac{\mathcal{B}[\bar{B} \to X_d\gamma]}{\mathcal{B}[\bar{B} \to X_s\gamma]}$ dominated by CKM uncertainties
- On top of these errors, $\mathcal{B}[\bar{B} \to X_d\gamma]$ is affected by non-perturbative u-quark loops, effect expected to be around 10%
- Another analysis by [Ali,Asatrian,Greub'98, updated '03],

$\lambda_i = V_{ib}V_{is}^*$, $\xi_i = V_{ib}V_{id}^*$, $D_i = f(m_{b,c}, \mu, \alpha_s)$

$$\frac{\langle\mathcal{B}(B \to X_d\gamma)\rangle}{\langle\mathcal{B}(B \to X_s\gamma)\rangle} = \frac{|\xi_t|^2}{|\lambda_t|^2} + \frac{D_u}{D_t}\,\frac{|\xi_u|^2}{|\lambda_t|^2} + \frac{D_r}{D_t}\,\frac{\mathrm{Re}(\xi_t^*\xi_u)}{|\lambda_t|^2} \simeq 3.6 \times 10^{-2}$$

CP asymmetries in $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_d\gamma$

- Direct CP asymmetry

$$A_{\rm CP}^{b\to q\gamma} \equiv \frac{\Gamma[\bar{B}\to X_q\gamma] - \Gamma[B\to X_{\bar{q}}\gamma]}{\Gamma[\bar{B}\to X_q\gamma] + \Gamma[B\to X_{\bar{q}}\gamma]}$$

- The SM predictions are [Hurth,Lunghi,Porod'03]

$$A_{\rm CP}^{b\to s\gamma} = \left[0.44\ {}^{+0.15}_{-0.10}\Big|_{\frac{m_c}{m_b}} \pm 0.03_{\rm CKM}\ {}^{+0.19}_{-0.09}\Big|_{\rm scale}\right]\%$$

$$A_{\rm CP}^{b\to d\gamma} = \left[-10.2\ {}^{+2.4}_{-3.7}\Big|_{\frac{m_c}{m_b}} \pm 1.0_{\rm CKM}\ {}^{+2.1}_{-4.4}\Big|_{\rm scale}\right]\%$$

- The additional parametric uncertainties are subdominant

- Other analysis [Ali,Asatrian,Greub'98, updated '03]

$$A_{\rm CP}^{b\to s\gamma} \simeq \frac{{\rm Im}(\lambda_t^*\lambda_u)\,D_i}{|\lambda_t|^2\,D_t} \sim 0.5\% \qquad A_{\rm CP}^{b\to d\gamma} \simeq \frac{{\rm Im}(\xi_t^*\xi_u)\,D_i}{|\xi_t|^2\,D_t} \sim -13\%$$

Untagged $\bar{B} \to X_{s+d}\,\gamma$ CP asymmetry

- Unnormalized CP asymmetry for the sum $b \to (s+d)\gamma$ vanishes in the U-spin limit $m_s = m_d$ [Soares'91]
- Hence, in the U-spin limit and for real Wilson coefficients one finds

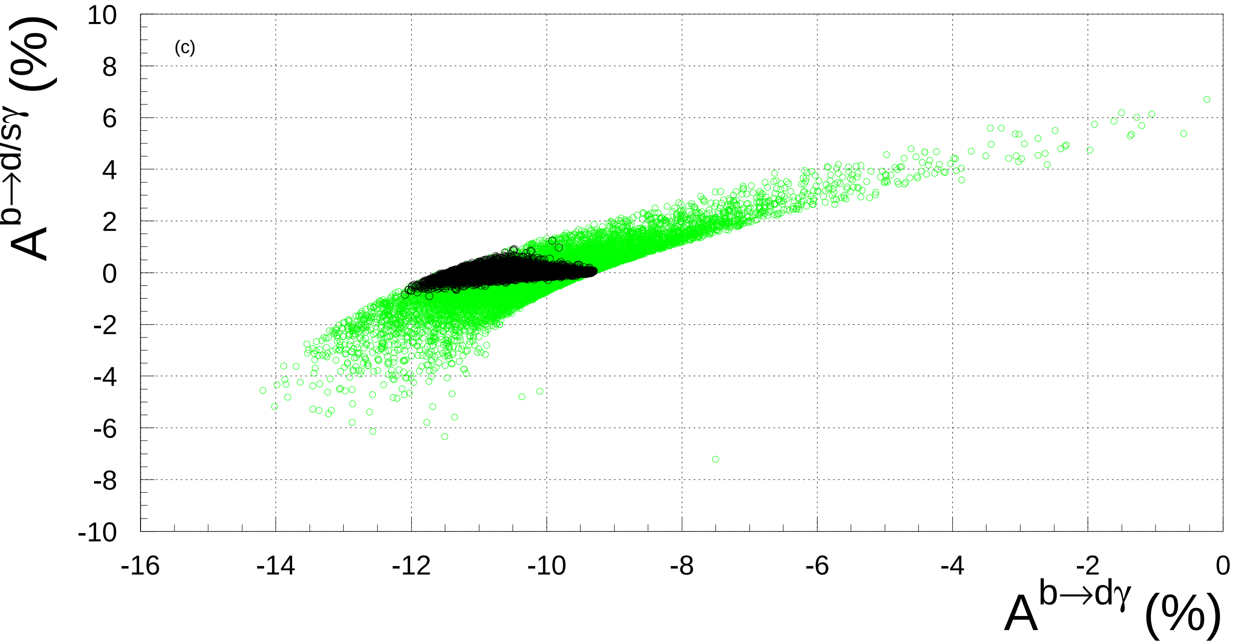
$$\left[\Gamma(\bar{B} \to X_s\,\gamma) - \Gamma(B \to X_{\bar{s}}\,\gamma)\right] + \left[\Gamma(\bar{B} \to X_d\,\gamma) - \Gamma(B \to X_{\bar{d}}\,\gamma)\right] = 0$$

- The size of the untagged $\bar{B} \to X_{s+d}\,\gamma$ CP asymmetry is a measure of U-spin breaking
- In the SM within the partonic contribution one finds [Hurth,Mannel'01]

$$|\Delta\mathcal{B}(B \to X_s\gamma) + \Delta\mathcal{B}(B \to X_d\gamma)| \sim 1 \cdot 10^{-9}$$

- Power corrections beyond the leading partonic contribution are expected to be small
  - U-spin breaking in $1/m_{b,c}^2$ corrections bring up a factor of m_s^2/m_b^2
  - Non-perturbative $1/m_u^2$ corrections scale like Λ/m_b and follow same pattern
- Any sizable value of this quantity is a direct signal for NP

Untagged $\bar{B} \to X_{s+d}\,\gamma$ CPA in BSM models



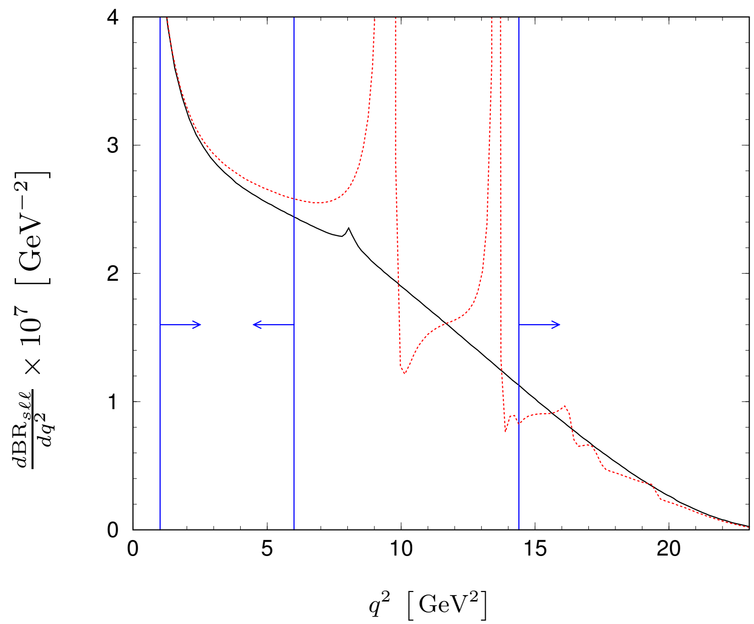
- Untagged rate asymmetry in MFV with flavour-blind phases without (green) and with (black) EDM contraints

  [Hurth,Lunghi,Porod'03]

- Exptl. accuracy of B-factories of untagged CPA ($\pm 3\%$) allows to distinguish between MFV and more general flavour models, where untagged CPA can reach $\sim 10\%$
- Distinction between MFV with and without flavour-blind phases not possible at existing, but within reach of future B facilities

Inclusive mode $\bar{B} \to X_d \ell^+ \ell^-$

- Richer kinematic structure than $\bar{B} \to X_d \gamma$. Three-body final state, presence of axial current.
- For $1 < q^2 < 6$ GeV^2 the ρ, ω, and $\bar{c}c$ resonances are cut out
- Cleaner than $\bar{B} \to X_d \gamma$ in this region since on-shell up-quark loops can be avoided



NNLO QCD predictions of $d\mathrm{BR}_{s\ell\ell}/dq^2$

[Ghinculov,Hurth,Isidori,Yao'03]

$$\mathcal{R}_{\text{quark}} = \int_{0.05}^{0.25} d\hat{s}\, R_{\text{quark}} = (4.75 \pm 0.25) \times 10^{-7}$$

[Asatrian,Bieri,Greub,Walker'03]

- Number is without power corrections and without taking into account resonances
- Important question: Can this be measured at SuperB ?

Exclusive modes $B \to \rho\gamma$

[Bosch,Buchalla'01; Ali,Parkhomenko'01]
[Beneke,Feldmann,Seidel'04]

- Factorization formula

$$\langle V\gamma(\epsilon)|O_i|\bar{B}\rangle = \left[F^{B\to V}(0)\,T_i^I + \int_0^1 d\xi\,dv\,T_i^{II}(\xi,v)\,\Phi_B(\xi)\,\Phi_V(v)\right]\cdot\epsilon$$

- Ratio of branching ratios $$\mathcal{R}(\rho\gamma/K^*\gamma) = S_\rho\left|\frac{V_{td}}{V_{ts}}\right|\left[\frac{M_B^2 - M_\rho^2}{M_B^2 - M_{K^*}^2}\right]^3\zeta^2(1+\Delta R)$$

- Isospin asymmetry $$\Delta(\rho\gamma) = \frac{\Delta^{+0}+\Delta^{-0}}{2}\,, \qquad \Delta^{\pm 0} = \frac{\Gamma(B^\pm\to\rho^\pm\gamma)}{2\Gamma(B^0\to\rho^0\gamma)} - 1$$

- Direct CP asymmetry $$\mathcal{A}_{CP}(\rho\gamma) = \frac{\Gamma(B\to\rho\gamma)-\Gamma(\bar{B}\to\rho\gamma)}{\Gamma(B\to\rho\gamma)+\Gamma(\bar{B}\to\rho\gamma)}$$

- Large weak annihilation contribution to exclusive $B^\pm\to\rho^\pm\gamma$, although formally of order $1/m_b$, but enhanced by large $C_7^{(u)} \sim 10\,C_7^{\rm eff}$.

Exclusive modes $B \to \rho\gamma$

[see also Bosch,Buchalla'01; Ali,Parkhomenko'01]

$$\mathcal{R}^{\pm}(\rho\gamma/K^*\gamma) = 0.023 \pm 0.012$$

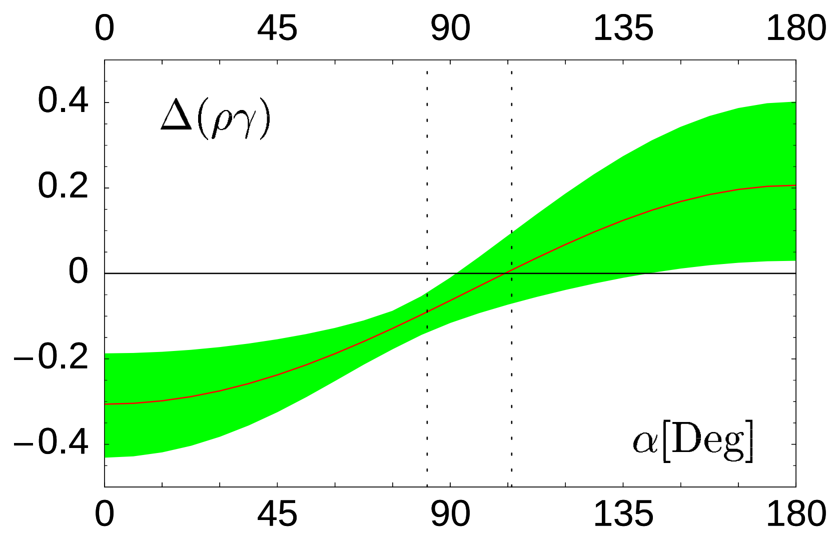
$$\mathcal{R}^{0}(\rho\gamma/K^*\gamma) = 0.011 \pm 0.006$$

$$\Delta(\rho\gamma) = 0.04^{+0.14}_{-0.07}$$

$$\mathcal{A}^{\pm}_{CP}(\rho\gamma) = 0.10^{+0.03}_{-0.02}$$

$$\mathcal{A}^{0}_{CP}(\rho\gamma) = 0.06 \pm 0.02$$

[Ali,Lunghi'02]



$$\mathrm{Br}(B^0 \to K^{*0}\gamma) = \left[\frac{T_1^{K^*}(0)}{0.38}\right]^2 (7.4\,^{+0.6}_{-0.5}|_{V_{ts}}\,^{+0.7}_{-0.7}|_{\mathrm{had}}) \cdot 10^{-5}$$

$$\mathrm{Br}(B^+ \to K^{*+}\gamma) = \left[\frac{T_1^{K^*}(0)}{0.38}\right]^2 (7.4\,^{+0.6}_{-0.5}|_{V_{ts}}\,^{+0.6}_{-0.7}|_{\mathrm{had}}) \cdot 10^{-5}$$

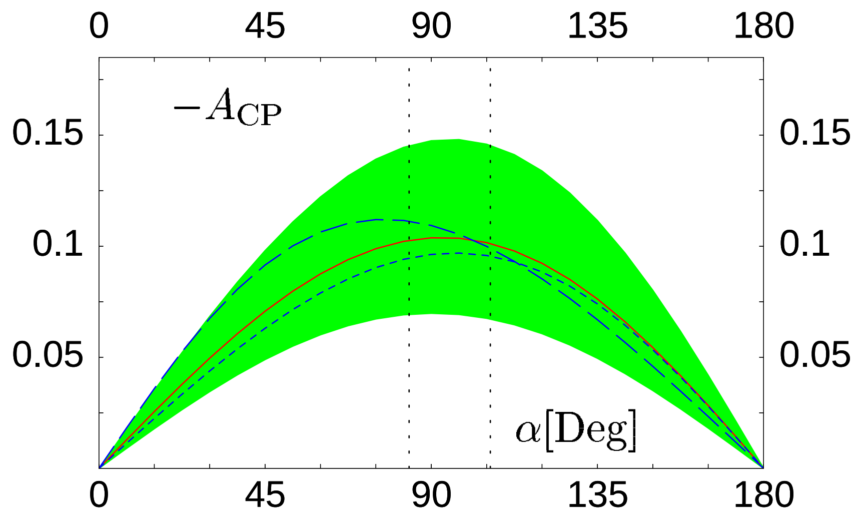
$$\mathrm{Br}(B^0 \to \rho^0\gamma) = \left(\frac{|V_{td}|}{8.25\cdot 10^{-3}}\right)^2 \left(\frac{T_1^{\rho}(0)}{0.21}\right)^2 (5.0^{+0.5}_{-0.5}) \cdot 10^{-7}$$

$$\mathrm{Br}(B^+ \to \rho^+\gamma) = \left(\frac{|V_{td}|}{8.25\cdot 10^{-3}}\right)^2 \left(\frac{T_1^{\rho}(0)}{0.21}\right)^2 (10.3^{+1.5}_{-1.2}) \cdot 10^{-7}$$

$$\Delta^{+0}(\rho\gamma) = (-4.6\,^{+5.4}_{-4.2}|_{\mathrm{CKM}}\,^{+5.8}_{-5.6}|_{\mathrm{had}})\%$$

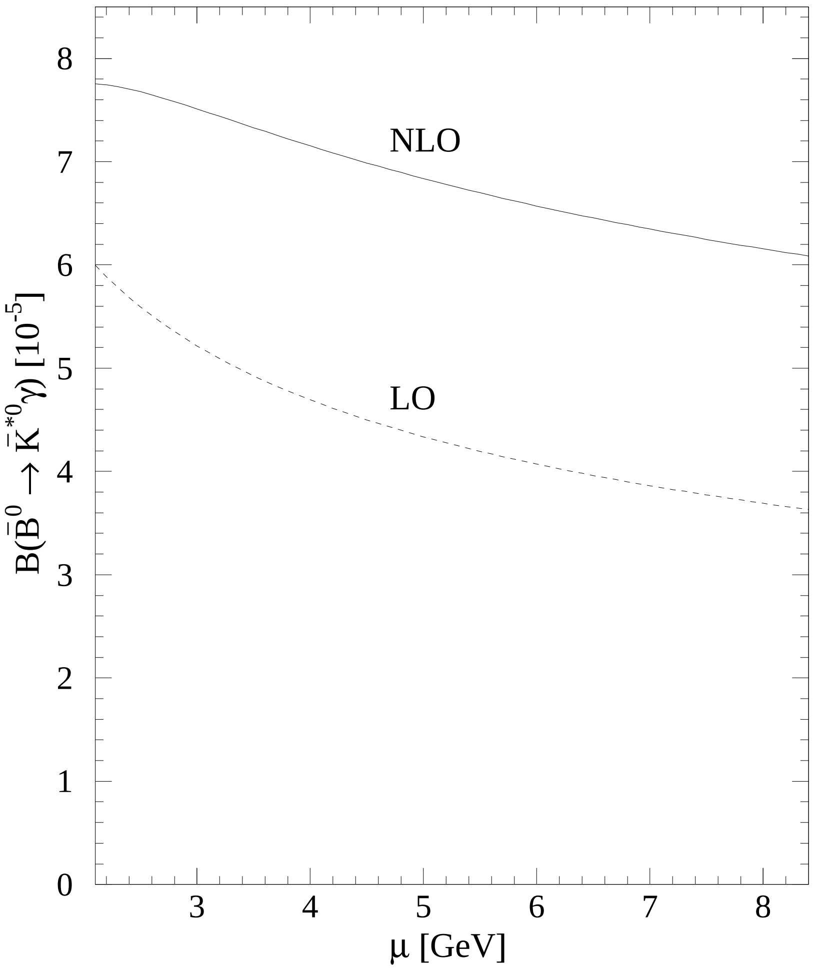
$$\mathcal{A}^{+}_{\mathrm{CP}}(\rho\gamma) = (10.7\,^{+2.0}_{-1.5}|_{\mathrm{CKM}}\,^{+3.7}_{-2.6}|_{\mathrm{had}})\,\%$$

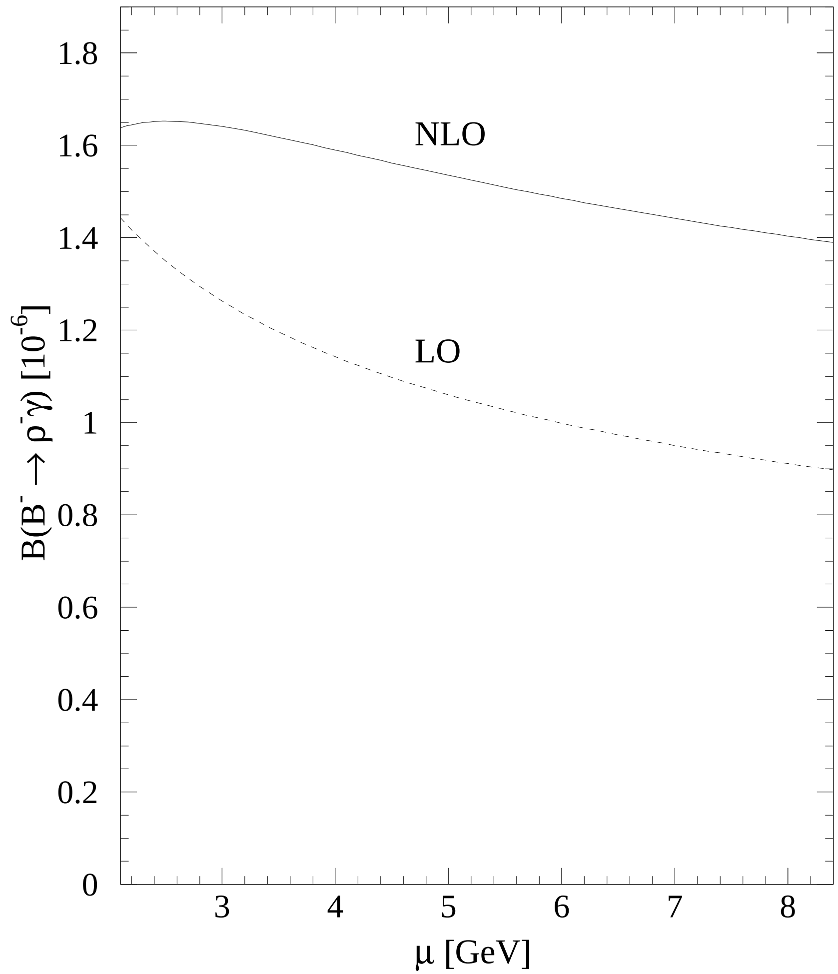
$$\mathcal{A}^{0}_{\mathrm{CP}}(\rho\gamma) = (10.4\,^{+2.4}_{-1.6}|_{\mathrm{CKM}}\,^{+3.6}_{-3.0}|_{\mathrm{had}})\,\%$$



[Beneke,Feldmann,Seidel'04]

Exclusive modes $B \to \rho\gamma$





[Bosch,Buchalla'01]

- Moreover: Determination of $|V_{td}/V_{ts}| = 0.194 \pm 0.029$ possible, precision will increase at SuperB

Exclusive modes $B \to \rho\, \ell^+ \ell^-$

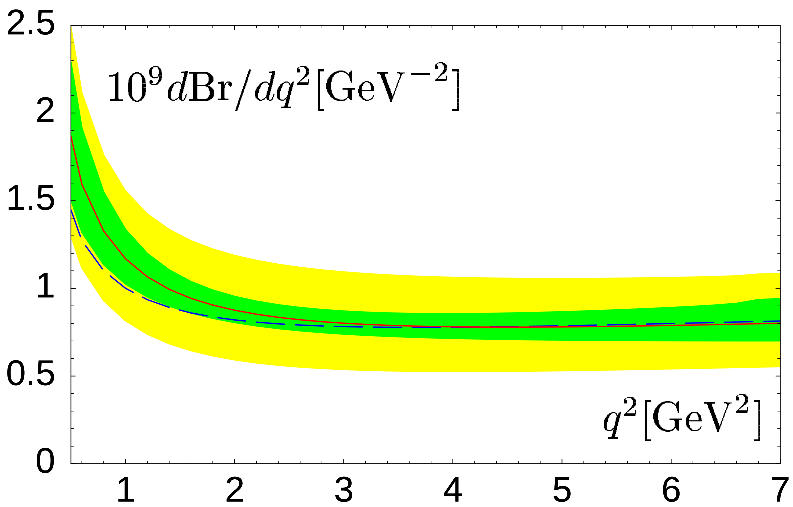
[Beneke,Feldmann,Seidel'04]

- $B \to V\, \ell^+ \ell^-$ branching fractions

$$\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2\, \frac{d\mathrm{Br}(B^+ \to K^{*+} \ell^+ \ell^-)}{dq^2} = \left[\frac{A_0^{K^*}(4\,\mathrm{GeV}^2)}{0.66}\right]^2 (3.33^{+0.40}_{-0.31}) \cdot 10^{-7}$$

$$\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2\, \frac{d\mathrm{Br}(B^0 \to \rho^0 \ell^+ \ell^-)}{dq^2} = \left[\frac{|V_{td}|}{8.25 \cdot 10^{-3}} \, \frac{A_0^{\rho}(4\,\mathrm{GeV}^2)}{0.50}\right]^2 (4.2^{+0.6}_{-0.4}) \cdot 10^{-9}$$

$$\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2\, \frac{d\mathrm{Br}(B^+ \to \rho^+ \ell^+ \ell^-)}{dq^2} = \left[\frac{|V_{td}|}{8.25 \cdot 10^{-3}} \, \frac{A_0^{\rho}(4\,\mathrm{GeV}^2)}{0.50}\right]^2 (9.6^{+1.5}_{-1.1}) \cdot 10^{-9}$$



- Yellow: Total error
- Green: Error on CKM and form factor excluded
- Dashed: LO

Exclusive modes $B \to \rho\, \ell^+ \ell^-$

- Forward-backward asymmetry and its zero, q_0^2, in GeV^2 [Beneke,Feldmann,Seidel'04]

$B^0 \to \rho^0\, \ell^+\ell^-$

$4.34\,{}^{+0.02}_{-0.02}\big|_{\rm CKM}\,{}^{+0.45}_{-0.39}\big|_{\rm had}$

$\bar{B}^0 \to \rho^0\, \ell^+\ell^-$

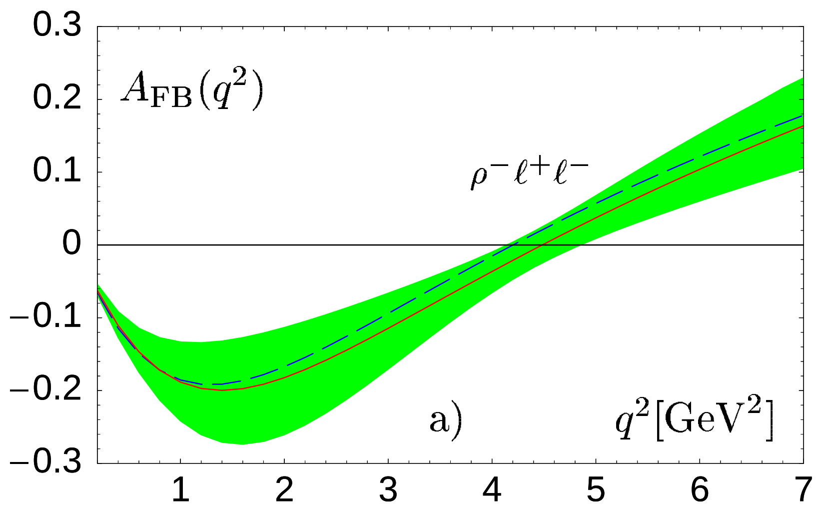
$4.11\,{}^{+0.02}_{-0.02}\big|_{\rm CKM}\,{}^{+0.26}_{-0.22}\big|_{\rm had}$

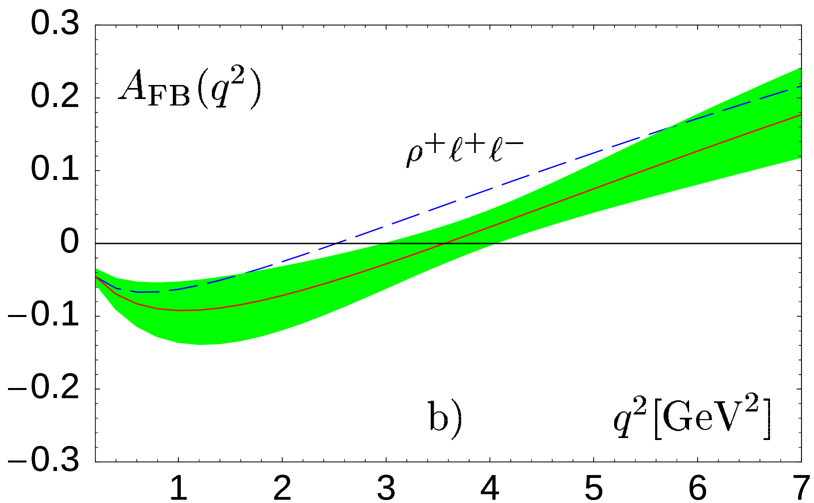
$B^+ \to \rho^+\, \ell^+\ell^-$

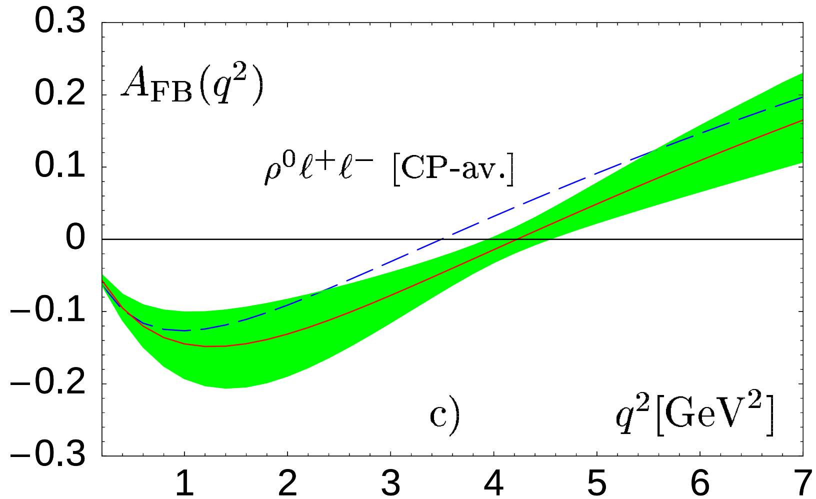
$3.56\,{}^{+0.09}_{-0.12}\big|_{\rm CKM}\,{}^{+0.48}_{-0.57}\big|_{\rm had}$

$B^- \to \rho^-\, \ell^+\ell^-$

$4.48\,{}^{+0.07}_{-0.06}\big|_{\rm CKM}\,{}^{+0.36}_{-0.34}\big|_{\rm had}$







- Significantly different FBA in neutral or charged B mesons due to important new contribution from $C_{9,\perp}^{(u)}$

Experimental reach at SuperB

Observable	B Factories ($2\ \mathrm{ab}^{-1}$)	SuperB ($75\ \mathrm{ab}^{-1}$)
$\mathrm{BR}(B \to \rho\gamma)$	15%	3% (†)
$\mathrm{BR}(B \to \omega\gamma)$	30%	5%
$A_{\mathrm{CP}}(B \to K^*\gamma)$	0.007 (†)	0.004 († $*$)
$A_{\mathrm{CP}}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{\mathrm{CP}}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{\mathrm{CP}}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K_{\mathrm{S}}\pi^0\gamma)$	0.15	0.02 ($*$)
$S(\rho^0\gamma)$	possible	0.10
$A_{\mathrm{CP}}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%

- † / $*$: systematics / theory limited

Conclusion

- Due to the democratic pattern of the CKM elements, $b \to d$ transitions offer an interesting and complementary phenomenology compared to $b \to s$ decays.
- Direct CP asymmetries small in $\bar{B} \to X_s\gamma$, but $\mathcal{O}(10)$% in $\bar{B} \to X_d\gamma$ in the SM
- CP asymmetry in untagged $\bar{B} \to X_{s+d}\gamma$ has the potential to serve as a Null test. Can this be exploited at SuperB?
- Exclusive $b \to d\gamma$ and $b \to d\,\ell^+\ell^-$ decays offer further observables (e.g. isospin asymmetries) and allow to determine $|V_{td}|/|V_{ts}|$
- Question: How well can $b \to d$ transitions be measured at SuperB? Is it worth pursuing inclusive $b \to d\gamma$ and $b \to d\,\ell^+\ell^-$ on the theoretical side?