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$B \to K^*\gamma$ and $B \to \rho\gamma$ at NLO from QCD Factorization

in collaboration with Gerhard Buchalla

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Introduction

radiative FCNC $b \to s\,(d)\,\gamma$ transition

- high sensitivity to New Physics
- large impact of SD QCD corrections
- experimentally accessible already at present

inclusive mode

- $B(B \to X_s\gamma)_{exp} = (3.41 \pm 0.36) \cdot 10^{-4}$

  ALEPH, BABAR, BELLE, CLEO

- HQE $\to$ perturbative calculation

  Adel, Yao
  Chetyrkin, Misiak, Münz
  Greub, Hurth, Wyler

exclusive mode

Greub, Simma, Wyler
Asatryan, Asatrian, Wyler
Grinstein, Pirjol

- $$\begin{aligned} B(B^0 \to K^{*0}\gamma)_{exp} &= (4.59 \pm 0.55) \cdot 10^{-5} \\ B(B^+ \to K^{*+}\gamma)_{exp} &= (3.82 \pm 0.78) \cdot 10^{-5} \\ B(B^0 \to \rho^0\gamma)_{exp} &< 1.5 \cdot 10^{-6} \text{ at 90\% C.L.} \\ B(B^+ \to \rho^+\gamma)_{exp} &< 2.8 \cdot 10^{-6} \end{aligned}$$

  CLEO, BELLE, BABAR

- bound state effects essential

  $\to$ nonperturbative hadronic form-factors

  $\to$ QCD factorization

  Beneke, Buchalla, Neubert, Sachrajda

  $\to$ systematic model-independent NLL framework

  Beneke, Feldmann, Seidel
  SWB, Buchalla

Basic Formulas for $B \to V\gamma$

Beneke, Feldmann, Seidel
Ali, Parkhomenko
SWB, Buchalla

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{p,i} \lambda_p^{\mathrm{CKM}} C_i(\mu)\, Q_i^p$$

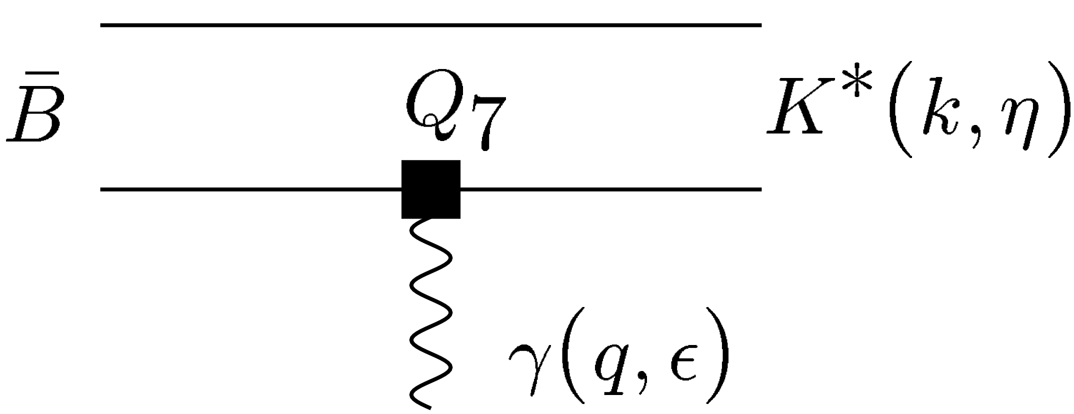
$$\begin{aligned}
Q^p_{\mathrm{cc}} &= (\bar{s}\, p)_{V-A} (\bar{p}\, b)_{V-A} \\
Q_{\mathrm{pen}} &= (\bar{s}p)_{V-A} \textstyle\sum_q (\bar{q}q)_{V\mp A} \\
Q_7 &= \frac{e}{8\pi^2} m_b\, \bar{s}\, \sigma^{\mu\nu}(1+\gamma_5) b\, F_{\mu\nu} \\
Q_8 &= \frac{g}{8\pi^2} m_b\, \bar{s}\, \sigma^{\mu\nu}(1+\gamma_5) T^a b\, G^a_{\mu\nu}
\end{aligned}$$

matrix elements $\langle V\gamma(\epsilon)|Q_i|\bar{B}\rangle$ in heavy quark limit $m_b \gg \Lambda_{QCD} \to$ factorization formula in ldg. power

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

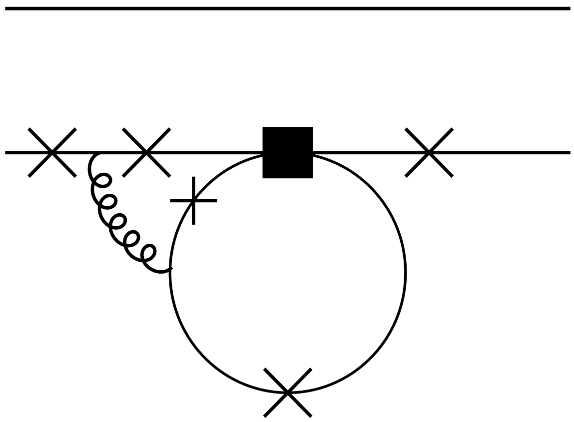
universal nonperturbative form factor and LCDAs factorized from perturbative hard-scattering kernels

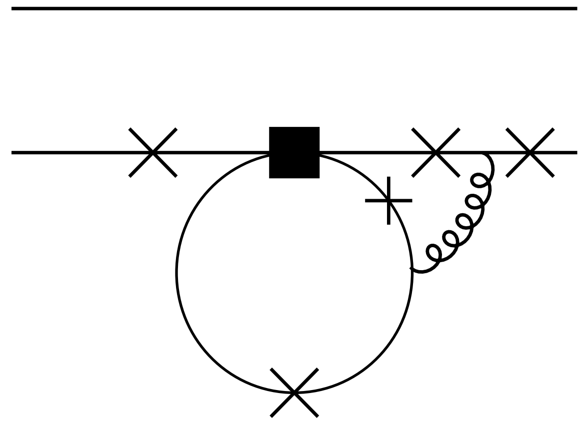
LO contribution from Q_7



$$\langle Q_7 \rangle = \frac{-e}{2\pi^2} m_b F_V \left[\varepsilon(\epsilon, \eta, k, q) + i(\epsilon\cdot\eta\, k\cdot q - \epsilon\cdot k\, \eta\cdot q) \right]$$

NLO type I



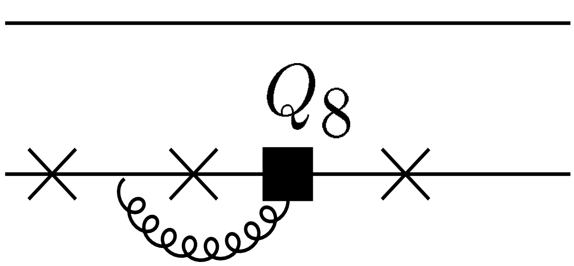


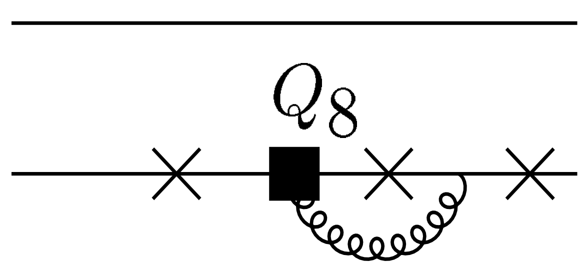
$$\langle Q_i \rangle^I \;=\; \langle Q_7 \rangle \frac{\alpha_s C_F}{4\pi} G_i$$

$$G_i(s_c) \;=\; l_i \ln \frac{\mu}{m_b} + g_i \underbrace{(s_c)}_{= m_c^2/m_b^2}$$

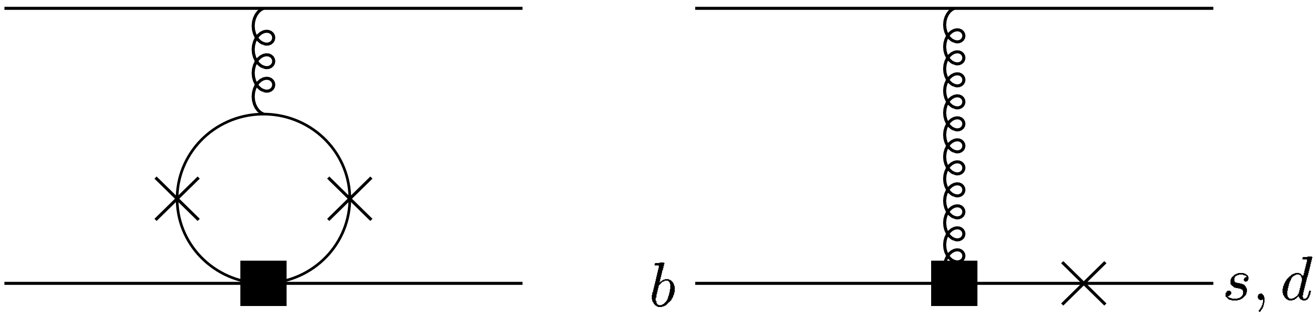
Greub, Hurth, Wyler
Buras, Czarnecki, Misiak, Urban

Dominated by hard scales $\sim m_b \to$ IR finite



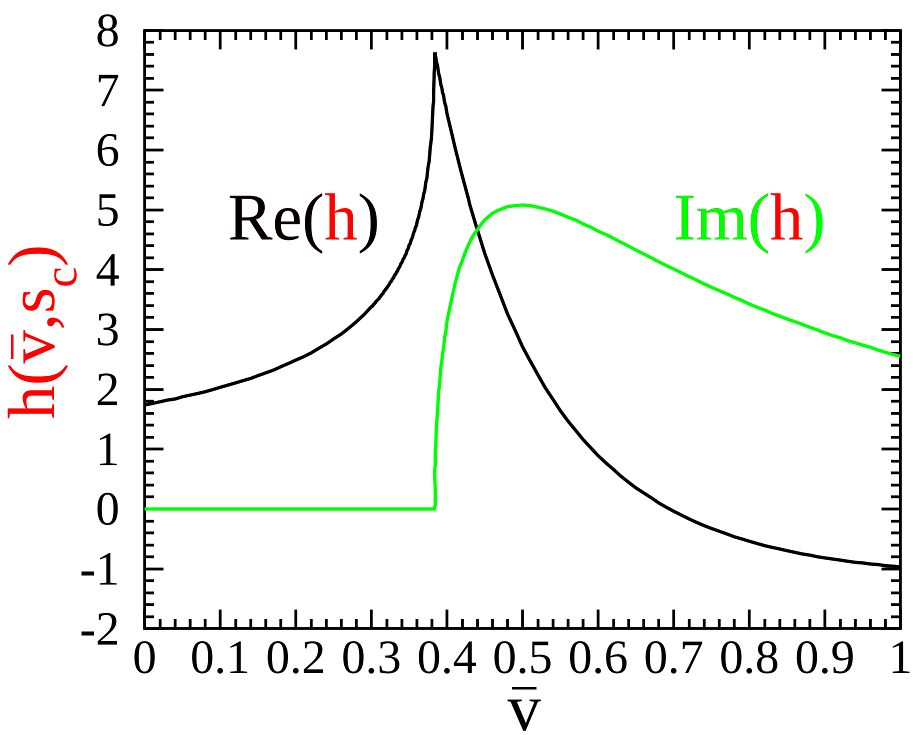


NLO type II



$$\langle Q_i \rangle^{II} = \langle Q_7 \rangle \frac{\alpha_s(\mu_h) C_F}{4\pi} H_i$$

$$H_1^V(s) = -\frac{2\pi^2}{3N} \frac{f_B f_V^\perp}{F_V m_B^2} \underbrace{\int_0^1 d\xi \frac{\Phi_{B1}(\xi)}{\xi}}_{=: m_B/\lambda_B} \int_0^1 dv\, h(\bar{v}, s) \Phi_\perp^V(v)$$



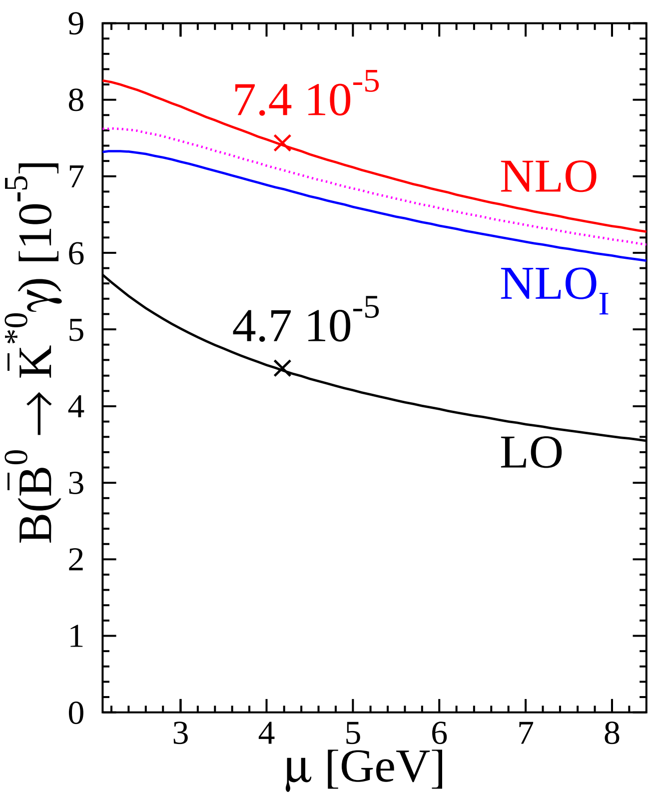
$$H_8^V = \frac{4\pi^2}{3N} \frac{f_B f_V^\perp}{F_V m_B^2} \int_0^1 d\xi \frac{\Phi_{B1}(\xi)}{\xi} \underbrace{\int_0^1 dv \frac{\Phi_\perp^V(v)}{v}}_{=3(1-\alpha_1^\perp+\alpha_2^\perp)}$$

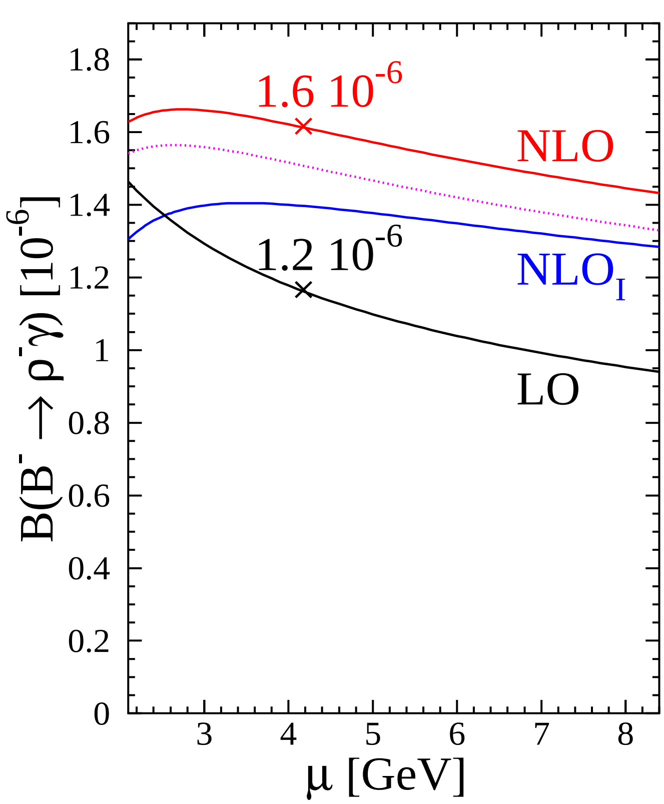
Results

$$A(\bar{B} \to V\gamma) = \frac{G_F}{\sqrt{2}} \left[\sum_{p=u,c} \lambda_p^{\mathrm{CKM}} a_7^p \right] \langle V\gamma | Q_7 | \bar{B} \rangle$$

$$a_7^p(V\gamma) = C_7 + \frac{\alpha_s(\mu) C_F}{4\pi} \sum_{i=1}^{8} C_i(\mu) G_i(s) + \frac{\alpha_s(\mu_h) C_F}{4\pi} \sum_{j=1}^{8} C_j(\mu_h) H_j^V$$

$$\begin{aligned} a_7^c(K^*\gamma) &= -0.322 + 0.011 \\ &\quad -0.079 - 0.013i \\ &\quad -0.017 - 0.012i \\ &= -0.407 - 0.025i \end{aligned}$$



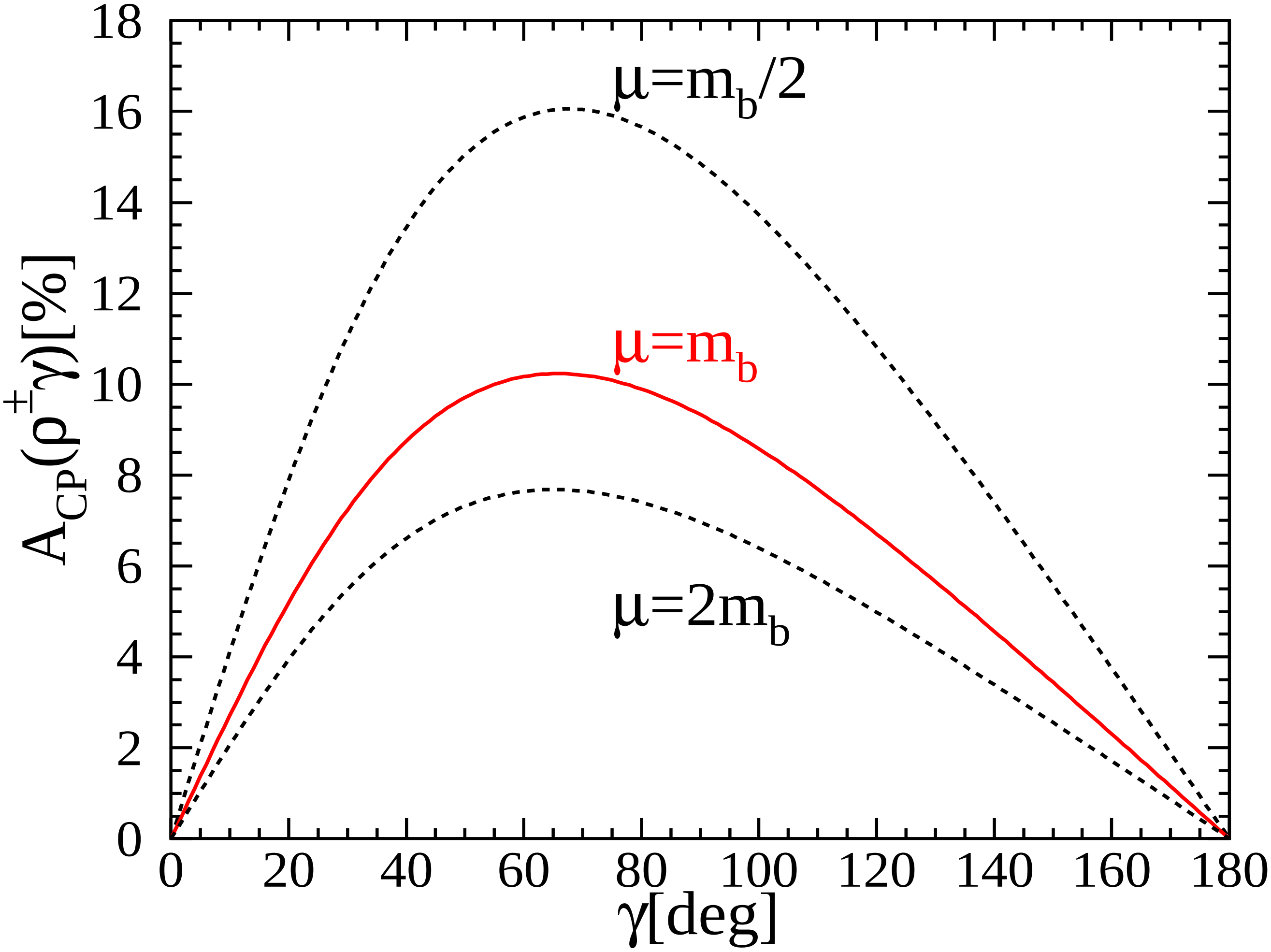


$B \to \rho\gamma$ Phenomenology

CP asymmetry

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

$$\approx \frac{2\,\mathrm{Im}\lambda_u^*\lambda_c}{|\lambda_t|^2}\,\frac{\mathrm{Im}a_7^{u*}a_7^c}{|C_7|^2}$$



Maximum at $\gamma \approx 65$ deg.

$\mathcal{A}_{CP}(K^{*0}\gamma) = -0.3\%$

Isospin breaking

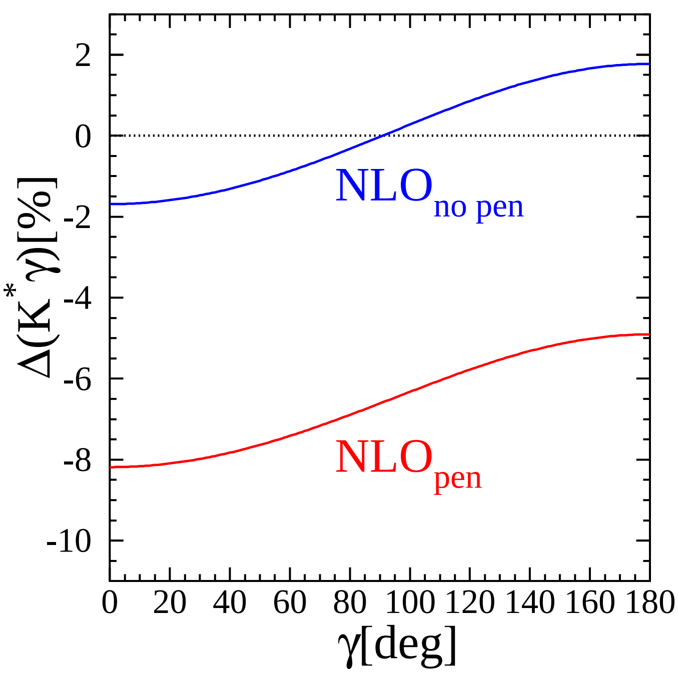
$$\Delta_{+0} = \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1$$

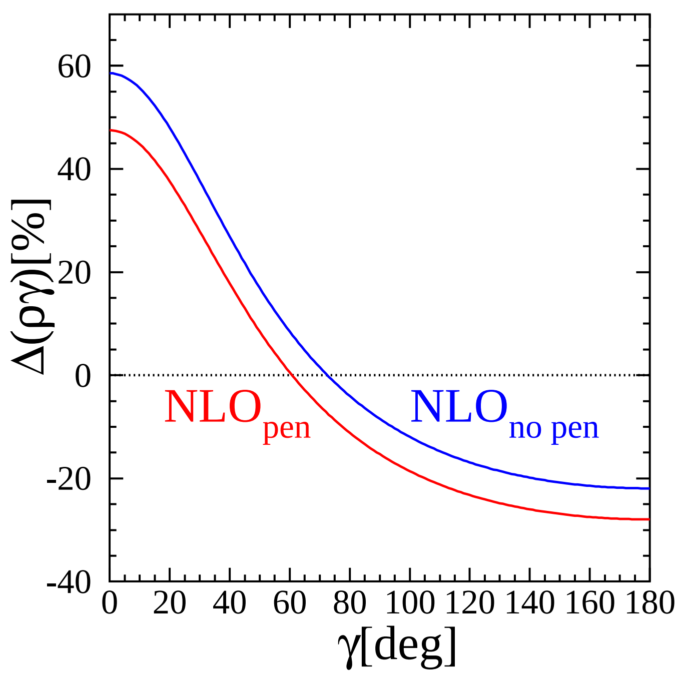
$$\Delta_{-0} = \frac{\Gamma(B^- \to \rho^-\gamma)}{2\Gamma(\bar{B}^0 \to \rho^0\gamma)} - 1$$

$$\Delta(V\gamma) = \frac{\Delta_{+0} + \Delta_{-0}}{2}$$

Ali, Handoko, London
SWB, Buchalla

large effect from Q_6 on $\Delta(K^*\gamma)$ Kagan, Neubert





$\Delta(K^*\gamma) = (-7.5^{+4.1}_{-5.9})\%$ $\Delta(\rho\gamma) = (2.0^{+27.0}_{-15.7})\%$

$$\Delta(K^*\gamma)_{\text{exp}} = (-19.2 \pm 11.8)\%$$

Summary

- systematic and model-independent framework for rare radiative decays $B \to V\gamma$ and $B \to \gamma\gamma$

- power counting in the heavy quark limit

- quark-loop contributions calculable in QCD factorization

- non-factorizable LD corrections power-suppressed

- strong phases from spectator interaction important for CP asymmetry

- weak annihilation in $B \to V\gamma$ power suppressed but numerically enhanced and calculable

- NLL: $B(\bar{B}^0 \to \bar{K}^{*0}\gamma) = (7.4^{+2.6}_{-2.4}) \cdot 10^{-5}$
  $B(B^- \to \rho^-\gamma) = (1.6^{+0.7}_{-0.5}) \cdot 10^{-6}$
  $\mathcal{A}_{CP}(\rho^\pm\gamma) \sim 10\%$
  LL: $B(\bar{B}_s \to \gamma\gamma) = (1.2^{+2.5}_{-0.7}) \cdot 10^{-6}$
  $B(\bar{B}_d \to \gamma\gamma) = (3.1^{+6.7}_{-2.1}) \cdot 10^{-8}$

- dominant uncertainty: non-perturbative input parameters (form factors, decay constants, λ_B)