Phenomenology of Two-Body Radiative B-Meson Decays

Alexander Parkhomenko

P.G. Demidov Yaroslavl State University, Yaroslavl

Conference on "Physics of Fundamental Interactions",
ITEP, Moscow, November 23, 2011

Outline

1. Introduction
2. Theoretical Basis
3. Phenomenology of $B \to K^*\gamma$ Decays
4. Phenomenology of $B \to (\rho, \omega)\gamma$ Decays
5. Summary

Based on the papers by

A. Ali and A.P., Eur. Phys. J. **C23** (2002) 89 [hep-ph/0105302]

A. Ali, E. Lunghi, and A.P., Phys. Lett. **B595** (2004) 323 [hep-ph/0405075]

A. Ali and A.P., hep-ph/0610149

Introduction

- Interest in $B \to (\rho, \omega)\gamma$ decays is motivated by their potential importance for getting information on the CKM matrix, in particular, to extract $|V_{td}|$ and UT angle α
- Contributions from tree and penguin operators are of comparable size in the decay amplitude and differ by a weak phase, so both branching fractions and different asymmetries are sensitive to the CKM matrix elements
- Different approaches have been applied for the analysis of $B \to V\gamma$ decays: QCD Factorization, Perturbative QCD approach, SCET Factorization, etc.
- Application of QCD Factorization to the $B \to V\gamma$ decays and comparison of results with existing experimental data is the main topic of this talk

Effective Electroweak Theory

- Weak interactions at energies $E \ll M_W, M_Z$ are most conveniently described by an effective theory
- This theory is derived from the SM by integrating out heavy particles – top quark, W- and Z-bosons, Higgs
- Lagrangian density includes all the other quark flavors

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}\times\text{QED}} + \mathcal{L}_{\text{weak}}^{b\to d} + \mathcal{L}_{\text{weak}}^{b\to s}$$

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

$$\mathcal{L}_{\text{weak}}^{b\to d} = -\frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(d)} \sum_j C_j(\mu)\mathcal{O}_j(\mu)$$

- $\mathcal{L}_{\text{weak}}^{b\to s}$ for $b \to s$ transition can be obtained from $\mathcal{L}_{\text{weak}}^{b\to d}$:
  1. $d \to s$ for the quark fields in all the operators $\mathcal{O}_j(\mu)$
  2. $\lambda_d^{(p)} \equiv V_{pb}V_{pd}^* \to \lambda_s^{(p)} \equiv V_{pb}V_{ps}^*$ in the CKM factors

$B \to V$ Transition Form Factors

General decomposition on Lorentz structures admits seven form factors of the momentum squared $q^2 = (P - p)^2$

$$\left\langle V(p, \varepsilon^*) | \bar{Q} \, \gamma^\mu b | \bar{B}(P) \right\rangle = \frac{2i \, V^{(V)}(q^2)}{M + m_V} \, \epsilon^{\mu\nu\rho\sigma} \, \varepsilon^*_\nu p_\rho P_\sigma$$

$$\left\langle V(p, \varepsilon^*) | \bar{Q} \, \gamma^\mu \gamma_5 b | \bar{B}(P) \right\rangle = A_1^{(V)}(q^2) \, (M + m_V) \left[\varepsilon^{*\mu} - \frac{(\varepsilon^* q)}{q^2} \, q^\mu \right]$$
$$- A_2^{(V)}(q^2) \, \frac{(\varepsilon^* q)}{M + m_V} \left[P^\mu + p^\mu - \frac{M^2 - m_V^2}{q^2} \, q^\mu \right] + 2 m_V \, A_0^{(V)}(q^2) \, \frac{(\varepsilon^* q)}{q^2} \, q^\mu$$

$$\left\langle V(p, \varepsilon^*) | \bar{Q} \, \sigma^{\mu\nu} q_\nu b | \bar{B}(P) \right\rangle = 2 \, T_1^{(V)}(q^2) \, \epsilon^{\mu\nu\rho\sigma} \, \varepsilon^*_\nu p_\rho P_\sigma$$

$$\left\langle V(p, \varepsilon^*) | \bar{Q} \, \sigma^{\mu\nu} \gamma_5 q_\nu b | \bar{B}(P) \right\rangle = -i \, T_2^{(V)}(q^2) \left[(M^2 - m_V^2) \, \varepsilon^{*\mu} - (\varepsilon^* q) \, (P + p)^\mu \right]$$
$$- i \, T_3^{(V)}(q^2) \, (\varepsilon^* q) \left[q^\mu - \frac{q^2}{M^2 - m_V^2} \, (P + p)^\mu \right]$$

Symmetry Relations in $B \to V$ Transitions

- The heavy quark symmetry and the large recoil limit of the final state meson allow the form-factors' reductions
- Neglecting terms $\sim m_V^2/M^2$, relations at $q^2 = 0$:

$$\frac{M}{M+m_V}\, V^{(V)}(0) = \frac{M+m_V}{M}\, A_1^{(V)}(0) = T_1^{(V)}(0) = T_2^{(V)}(0) = \xi_\perp^{(V)}(0)$$

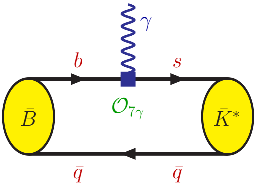
$$\frac{2m_V}{M}\, A_0^{(V)}(0) = \frac{M+m_V}{M}\, A_1^{(V)}(0) - \frac{M-m_V}{M}\, A_2^{(V)}(0) = T_2^{(V)}(0) - T_3^{(V)}(0) = \xi_\parallel^{(V)}(0)$$

- Valid for soft contributions (neglecting corrections $\sim 1/M$ and $\sim \alpha_s$)
- Factorization scheme is required ("soft form factors" renormalization conventions);
  holds exactly to all orders in perturbation theory

$$V^{(V)}(0) \equiv \frac{M+m_V}{M}\, \xi_\perp^{(V)}(0) \qquad A_0^{(V)}(0) \equiv \frac{M}{2m_V}\, \xi_\parallel^{(V)}(0)$$

$B \to K^*\gamma$ Branching Fraction in LO

- In the leading order, the penguin operator $\mathcal{O}_{7\gamma}$ contributes only
- Form-factor symmetry relation: $T_1^{(K^*)}(0) = T_2^{(K^*)}(0)$



- Branching fraction

$$\mathcal{B}_{\rm th}^{\rm LO}(B \to K^*\gamma) = \tau_B \frac{G_F^2 |V_{tb} V_{ts}^*|^2 \alpha M^3}{32\pi^4} \, \bar{m}_b^2(\mu_b) \, |C_7^{(0)\rm eff}(\mu_b)|^2 \, |T_1^{(K^*)}(0, \mu_b)|^2$$

- The b-quark mass $\bar{m}_b(\mu_b)$ and Wilson coefficient $C_7^{(0)\rm eff}(\mu_b)$ are dependent on the scale $\mu_b = \mathcal{O}(m_b)$; to compensate it, one should assume μ_b-dependence in $T_1^{(K^*)}(0, \mu_b)$

$B \to K^*\gamma$ Branching Fraction in NLO

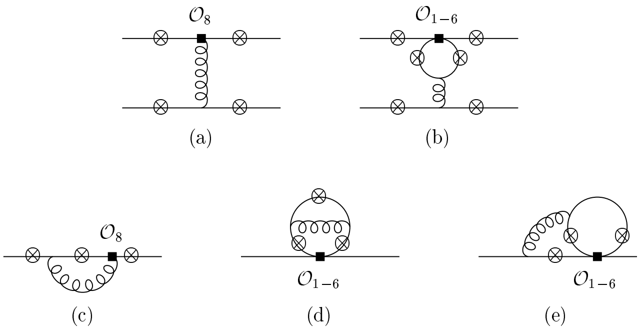
$$\mathcal{B}_{\rm th}(B \to K^*\gamma) = \tau_B \, \frac{G_F^2 \alpha |V_{tb} V_{ts}^*|^2}{32\,\pi^4} \, m_{b,\rm pole}^2 \, M^3 \, \left[\xi_\perp^{(K^*)}(0)\right]^2 \left| C_7^{(0)\rm eff}(\mu) + A^{(1)}(\mu) \right|^2$$

The function $A^{(1)}(\mu)$ includes all the NLO corrections

$$A^{(1)}(\mu) = A_{C_7}^{(1)}(\mu) + A_{\rm ver}^{(1)}(\mu) + A_{\rm sp}^{(1)K^*}(\mu_{\rm sp})$$

- $A_{C_7}^{(1)}(\mu)$ – $\mathcal{O}(\alpha_s)$ corrections from Wilson coefficient $C_7^{\rm eff}(\mu)$ and $\bar{m}_b(\mu)$
- $A_{\rm ver}^{(1)}(\mu)$ – $\mathcal{O}(\alpha_s)$ correction to the $b \to s\gamma$ vertex
- $A_{\rm sp}^{(1)K^*}(\mu_{\rm sp})$ – $\mathcal{O}(\alpha_s)$ hard-spectator contribution evaluated at intermediate scale $\mu_{\rm sp} = \sqrt{\mu\Lambda_{\rm H}}$ with $\Lambda_{\rm H} \simeq 0.5$ GeV

Nonfactorizable α_s Corrections



- First line: hard-spectator corrections
- Second line: $b \to s\gamma$ vertex corrections

Phenomenological Evaluation of $\xi_\perp^{(K^*)}(0)$

- $\mathcal{B}(B^+ \to K^{*+}\gamma)$ $\quad\xi_\perp^{(K^*)}(0) = 0.286 \pm 0.025$
- $\mathcal{B}(B^0 \to K^{*0}\gamma)$ $\quad\xi_\perp^{(K^*)}(0) = 0.291 \pm 0.024$

Average $\quad\bar{\xi}_\perp^{(K^*)}(0) = 0.289 \pm 0.025$

Full QCD form factor

$$T_1^{(K^*)}(0,\mu) = \xi_\perp^{(K^*)}(0)\left\{1 + \frac{\alpha_s(\mu)}{4\pi}\, C_F \left[\ln\frac{m_b^2}{\mu^2} - 1\right]\right\} + \frac{\alpha_s(\mu_{\rm sp})}{8\pi}\, C_F\, \Delta F_\perp^{(V)}(\mu_{\rm sp})$$

$$\bar{T}_1^{(K^*)}(0,\bar{m}_b) \simeq 1.05\,\bar{\xi}_\perp^{(K^*)}(0) = 0.303 \pm 0.026$$

LCSR $\quad T_1^{(K^*)}(0) = 0.31 \pm 0.04 \quad$ [Ball, Jones & Zwicky (2007)]

$B \to (\rho, \omega)\gamma$ Branching Fraction in NLO

- Charged-conjugate averaged branching ratio in the NLO

$$
\begin{aligned}
\bar{\mathcal{B}}_{\rm th}(B^\pm \to \rho^\pm\gamma) &= \tau_{B^+} \frac{G_F^2\alpha}{32\pi^4} \left|V_{tb}V_{td}^*\right|^2 m_{b,{\rm pole}}^2 M^3 \left[\xi_\perp^{(\rho)}(0)\right]^2 \\
&\times \Big\{ (C_7^{(0){\rm eff}} + A_R^{(1)t})^2 + (F_1^2 + F_2^2)\,(A_R^u + L_R^u)^2 \\
&+ 2F_1\,[C_7^{(0){\rm eff}}(A_R^u + L_R^u) + A_R^{(1)t} L_R^u] \Big\}
\end{aligned}
$$

- In CKM elements' ratio, $F_1 \propto \cos\alpha \simeq 0$ for $\alpha \simeq 90^\circ$

$$
V_{ub}V_{ud}^*/V_{tb}V_{td}^* = F_1 + iF_2 = -(R_u/R_t)\,{\rm e}^{i\alpha}
$$

- Amplitude $A^{(1)t}(\mu) = A_{C_7}^{(1)}(\mu) + A_{\rm ver}^{(1)}(\mu) + A_{\rm sp}^{(1)\rho}(\mu_{\rm sp})$
- The u-quark contribution $A^u(\mu) = A_{\rm ver}^u(\mu) + A_{\rm sp}^u(\mu_{\rm sp})$ from penguins can no longer be ignored
- Annihilation contributions $L_R^u = \epsilon_A\, C_7^{(0){\rm eff}}$; counts as $\Lambda_{\rm QCD}/m_b$ in the heavy-quark limit

$B \to (\rho, \omega)\gamma$ Branching Fractions

- Ratio of $B \to \rho\gamma$ ($B \to \omega\gamma$) and $B \to K^*\gamma$ decay widths is preferable; normalized by the experimental value of $B \to K^*\gamma$ branching fraction

$$\frac{\overline{\mathcal{B}}_{\rm th}(B \to \rho(\omega)\gamma)}{\overline{\mathcal{B}}_{\rm th}(B \to K^*\gamma)} = S_{\rho(\omega)} \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{(M^2 - m_{\rho(\omega)}^2)^3}{(M^2 - m_{K^*}^2)^3} \, \zeta_{\rho(\omega)}^2 \, [1 + \Delta R(\rho(\omega)/K^*)]$$

- Factors: $S_{\rho^\pm} = 1$; $S_{\rho^0} = 1/2$; $S_\omega = 1/2$
- ζ_ρ and ζ_ω are ratios of Effective theory form factors; in $SU(3)_{\rm F}$-symmetry limit, $\zeta_\rho = 1$ and $\zeta_\omega = 1$
- $SU(3)_{\rm F}$-breaking effects in QCD form factors $T_1^{(K^*)}(0)$, $T_1^{(\rho)}(0)$, and $T_1^{(\omega)}(0)$ evaluated within the QCD sum-rules

$$\zeta_\rho = \frac{T_1^{(\rho)}(0)}{T_1^{(K^*)}(0)} \simeq \frac{\xi_\perp^{(\rho)}(0)}{\xi_\perp^{(K^*)}(0)} = 0.86 \pm 0.07; \; \zeta_\omega = \frac{T_1^{(\omega)}(0)}{T_1^{(K^*)}(0)} \simeq \frac{\xi_\perp^{(\omega)}(0)}{\xi_\perp^{(K^*)}(0)} = 0.77 \pm 0.06$$

$B \to (\rho, \omega)\gamma$ Branching Fractions

- Ratio of CKM matrix elements from CKM unitarity

$$|V_{td}/V_{ts}| = 0.2061 \pm 0.0012^{+0.0080}_{-0.0060} \qquad \text{[PDG, 2011]}$$

- Branching ratios (in units of 10^{-6})

$$\bar{\mathcal{B}}_{\rm th}(B^\pm \to \rho^\pm\gamma) = 1.52 \pm 0.29[\rm th] \pm 0.06[\rm exp]$$
$$\bar{\mathcal{B}}_{\rm th}(B^0 \to \rho^0\gamma) = 0.72 \pm 0.14[\rm th] \pm 0.03[\rm exp]$$
$$\bar{\mathcal{B}}_{\rm th}(B^0 \to \omega\gamma) = 0.58 \pm 0.11[\rm th] \pm 0.02[\rm exp]$$

Mode	BABAR (465 M)	BELLE (657 M)	Average [PDG]
$B^+ \to \rho^+\gamma$	$1.20^{+0.42}_{-0.37} \pm 0.20$	$0.87^{+0.29}_{-0.27}{}^{+0.09}_{-0.11}$	0.98 ± 0.25
$B^0 \to \rho^0\gamma$	$0.97^{+0.24}_{-0.24} \pm 0.06$	$0.78^{+0.17}_{-0.16}{}^{+0.09}_{-0.10}$	0.86 ± 0.15
$B^0 \to \omega\gamma$	$0.50^{+0.27}_{-0.23} \pm 0.09$	$0.40^{+0.19}_{-0.17} \pm 0.13$	$0.44^{+0.18}_{-0.16}$

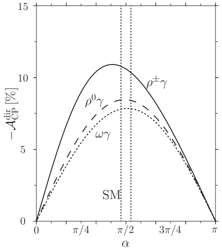
- Data and SM are in agreement, but not precisely so due to statistics

Direct CP-Asymmetry

- Direct CP-asymmetry in the $B^\pm \to \rho^\pm\gamma$ decay rates

$$\mathcal{A}_{\rm CP}(\rho^\pm\gamma) = \frac{\mathcal{B}(B^- \to \rho^-\gamma) - \mathcal{B}(B^+ \to \rho^+\gamma)}{\mathcal{B}(B^- \to \rho^-\gamma) + \mathcal{B}(B^+ \to \rho^+\gamma)}$$

  - Similar definitions in other two modes $B^0 \to \rho^0\gamma$ and $B^0 \to \omega\gamma$
  - CP-asymmetry arises from interference of penguin operator $\mathcal{O}_{7\gamma}$ and four-quark operators $\mathcal{O}_1$ and $\mathcal{O}_2$

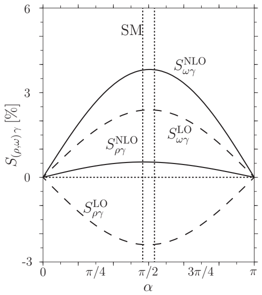


- Angle α known precisely $\alpha = (90.0 \pm 5.0)^\circ$ [PDG, 2010]

Mode	SM Pred.	Belle (657M)
$B^\pm \to \rho^\pm\gamma$	$(-10.6 \pm 2.8)\%$	$(-11 \pm 32 \pm 9)\%$
$B^0 \to \rho^0\gamma$	$(-8.5^{+3.7}_{-3.4})\%$	$(-44 \pm 49 \pm 14)\%$
$B^0 \to \omega\gamma$	$(-7.9^{+3.9}_{-3.4})\%$	

Mixing-Induced CP-Asymmetry

- Time-dependent CP-asymmetry in neutral B-meson decays involves the interference of $B^0 - \bar{B}^0$ mixing and decay amplitudes



$$a_{\rm CP}^{\rho\gamma}(t) = \mathcal{A}_{\rm CP}^{\rm dir}(\rho^0\gamma)\cos(\Delta M_d\, t) + S_{\rho\gamma}\sin(\Delta M_d\, t)$$

- Mixing-induced CP-asymmetry is

$$S_{\rho\gamma} = \frac{2\,{\rm Im}(\lambda_{\rho\gamma})}{1+|\lambda_{\rho\gamma}|^2}, \quad \lambda_{\rho\gamma} \equiv \frac{q}{p}\,\frac{A(\bar{B}_d^0 \to \rho^0\gamma)}{A(B_d^0 \to \rho^0\gamma)}$$

- In the SM, $q/p = {\rm e}^{-2i\beta}$ to a good approximation
- Similar definitions can be written for $B^0 \to \omega\gamma$
- SM estimates: $S^{\rm NLO}_{\rho\gamma} = (+0.5^{+4.1}_{-3.7})\%$ $\quad S^{\rm NLO}_{\omega\gamma} = (+3.8^{+4.4}_{-4.0})\%$
- Experimental value (657M) $\quad S^{\rm Belle}_{\rho\gamma} = (-83 \pm 65 \pm 18)\%$

Isospin-Violating Ratio

- Isospin-violating ratios in $B \to \rho\gamma$ decays are defined as

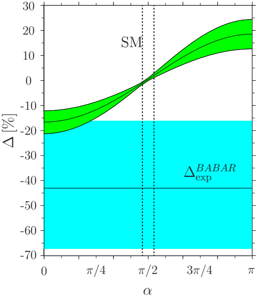
$$\Delta^{+0} = \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 \qquad \Delta^{-0} = \frac{\Gamma(B^- \to \rho^-\gamma)}{2\Gamma(\bar{B}^0 \to \rho^0\gamma)} - 1$$

- Charged-conjugate averaged ratio

$$\Delta = \frac{1}{2}\left[\Delta^{+0} + \Delta^{-0}\right]$$

- In the leading order in α_s

$$\Delta_{\rm LO} = -2\epsilon_A^{(\pm)}\,|\lambda_u|\cos\alpha + (\epsilon_A^{(\pm)})^2\,|\lambda_u|^2$$



- SM value is small $[\epsilon_A^{(\pm)} = 0.30 \pm 0.07]$

$\Delta_{\rm th}^{\rm SM} = (0.7^{+1.8}_{-1.2})\%$ origine: $\alpha = (90 \pm 5)^\circ$ [PDG, 2010]

- Current BABAR (465M) & BELLE (657M) measurements

$$\Delta_{\rm exp}^{\rm BaBar} = (-43^{+25}_{-22} \pm 10)\% \qquad \Delta_{\rm exp}^{\rm Belle} = (-48^{+21}_{-19}{}^{+8}_{-9})\%$$

$SU(3)_{\rm F}$-averaged $B \to (\rho, \omega)\gamma$ Branching Ratio

- Definitions of the averaging procedures

$$\bar{\mathcal{B}}(B \to \rho\gamma) \equiv \frac{1}{2}\,\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\,\mathcal{B}(B_d^0 \to \rho^0\gamma)$$

$$\bar{\mathcal{B}}[B \to (\rho, \omega)\,\gamma] \equiv \frac{1}{2}\left\{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\left[\mathcal{B}(B_d^0 \to \rho^0\gamma) + \mathcal{B}(B_d^0 \to \omega\gamma)\right]\right\}$$

- Combinations of the branching fractions results

$$\bar{\mathcal{B}}_{\rm th}(B \to \rho\gamma) = (1.53 \pm 0.30) \times 10^{-6}$$

$$\bar{\mathcal{B}}_{\rm th}[B \to (\rho, \omega)\gamma] = (1.46 \pm 0.28) \times 10^{-6}$$

- Good agreement with experiment within current errors

Branching ratios (in units of 10^{-6}) [PDG, 2010]

Mode	BABAR (465M)	BELLE (657M)	Average [PDG]
$B \to \rho\gamma$	$1.73^{+0.34}_{-0.32} \pm 0.17$	$1.21^{+0.24}_{-0.22} \pm 0.12$	$1.39^{+0.22}_{-0.21}$
$B \to (\rho, \omega)\gamma$	$1.63^{+0.30}_{-0.28} \pm 0.16$	$1.14 \pm 0.20^{+0.10}_{-0.12}$	$1.30^{+0.18}_{-0.19}$

Summary

- Branching fractions of $B \to V\gamma$ (K^*, ρ, ω) predicted in the SM are in agreement with the experimental data within erros
- Charged-conjugate average, Δ, of the isospin-violating ratios for the decays $B \to \rho\gamma$ are found to be $|\Delta| \leq 3\%$ in the expected range of CKM parameters. Experimental measurements are not precise to test it
- Direct CP asymmetries in the $B \to (\rho, \omega)\gamma$ decays are close to 10% but uncertainties are rather large which requires further theoretical improvements
- Mixing-induced CP-asymmetry $S_{\rho\gamma}$ is highly suppressed in the $B^0 \to \rho^0\gamma$ decay due to destructive interference of LO and NLO contributions. In the $B^0 \to \omega\gamma$ decay mode, $S_{\omega\gamma}$ is completely quantified and can be up to 10%

Backup Slides

$|V_{td}/V_{ts}|$ from $\bar{R}_{\rm exp}[(\rho,\omega)\,\gamma/K^*\gamma]$ Ratio

- $|V_{td}/V_{ts}|$ can be extracted from [A. Ali & AP (2004)]

$$\bar{R}_{\rm exp}[(\rho,\omega)\gamma/K^*\gamma] = \frac{\bar{\mathcal{B}}_{\rm exp}[B \to (\rho,\omega)\,\gamma]}{\bar{\mathcal{B}}_{\rm exp}(B \to K^*\gamma)} = r_{\rm th}^{(\rho/\omega)} \left|\frac{V_{td}}{V_{ts}}\right|^2 \zeta_\rho^2$$

$$r_{\rm th}^{(\rho/\omega)} = \frac{(M_B^2 - m_\rho^2)^3}{(M_B^2 - m_{K^*}^2)^3}\,[1 + \Delta R(\bar\rho,\bar\eta,\ldots)] \simeq 0.984 \pm 0.075$$

- Using $\zeta_\rho = 0.86 \pm 0.07$ [Ball, Jones & Zwicky (2007)]

$$\bar{R}_{\rm exp}^{\rm BELLE} = 0.0284 \pm 0.0050^{+0.0027}_{-0.0029} \Longrightarrow \left|\frac{V_{td}}{V_{ts}}\right| = 0.195^{+0.020}_{-0.019} \pm 0.015$$

$$\bar{R}_{\rm exp}^{\rm BABAR} = 0.039 \pm 0.008 \Longrightarrow \left|\frac{V_{td}}{V_{ts}}\right| = 0.233^{+0.025+0.022}_{-0.024-0.021}$$

- From ΔM_s measurements and Lattice-QCD

$$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007({\rm exp})^{+0.0081}_{-0.0060}({\rm th}) \quad \text{[CDF Collab.]}$$

$$|V_{td}/V_{ts}| = 0.2018 \pm 0.0050({\rm exp})^{+0.0079}_{-0.0059}({\rm th}) \quad \text{[D0 Collab.]}$$

Experimental Data on $B \to K^*\gamma$ and $B \to X_s\gamma$ Decays

Branching ratios (in units of 10^{-6})

Quantity	BABAR	BELLE	CLEO	Average
$\mathcal{B}(B^+ \to K^{*+}\gamma)$	$42.2 \pm 1.4 \pm 1.6$	$42.5 \pm 3.1 \pm 2.4$	$37.6^{+8.9}_{-8.3} \pm 2.8$	42.1 ± 1.8
$\mathcal{B}(B^0 \to K^{*0}\gamma)$	$44.7 \pm 1.0 \pm 1.6$	$40.1 \pm 2.1 \pm 1.7$	$45.5^{+7.2}_{-6.8} \pm 3.4$	43.3 ± 1.5
$\mathcal{B}(B \to K^*\gamma)$	48.2 ± 1.5	42.7 ± 2.4	43.2 ± 6.2	46.5 ± 1.3
$\mathcal{B}(B \to X_s\gamma)$	$327 \pm 18^{+55}_{-41}$	$345 \pm 15 \pm 40$	$321 \pm 43^{+32}_{-29}$	$355 \pm 24 \pm 9$
$R(K^*\gamma/X_s\gamma)$	$0.147^{+0.028}_{-0.021}$	$0.131^{+0.015}_{-0.013}$	$0.135^{+0.033}_{-0.027}$	0.135 ± 0.011

$$\bar{\mathcal{B}}(B \to K^*\gamma) \equiv \frac{1}{2}\left[\mathcal{B}(B^+ \to K^{*+}\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\mathcal{B}(B^0 \to K^{*0}\gamma)\right]$$

$$R(K^*\gamma/X_s\gamma) \equiv \frac{\bar{\mathcal{B}}(B \to K^*\gamma)}{\mathcal{B}(B \to X_s\gamma)}$$

Life-time ratio $\tau_{B^+}/\tau_{B^0} = 1.079 \pm 0.007$