pQCDを用いた$B \to \rho\gamma$ 崩壊の解析、Unitary 三角形に対する考察

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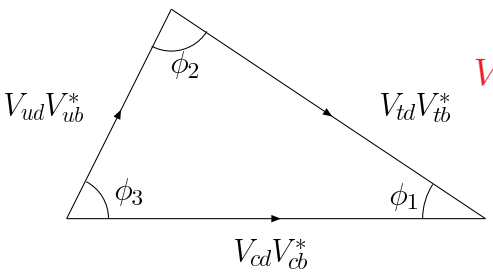
1. Introduction
2. pQCD の簡単な review
3. $B \to \rho\gamma$ 崩壊の解析
4. Unitary 三角形に対する考察

1. Introduction

標準模型の検証 $\Longrightarrow$ KEKやSLACのBファクトリー

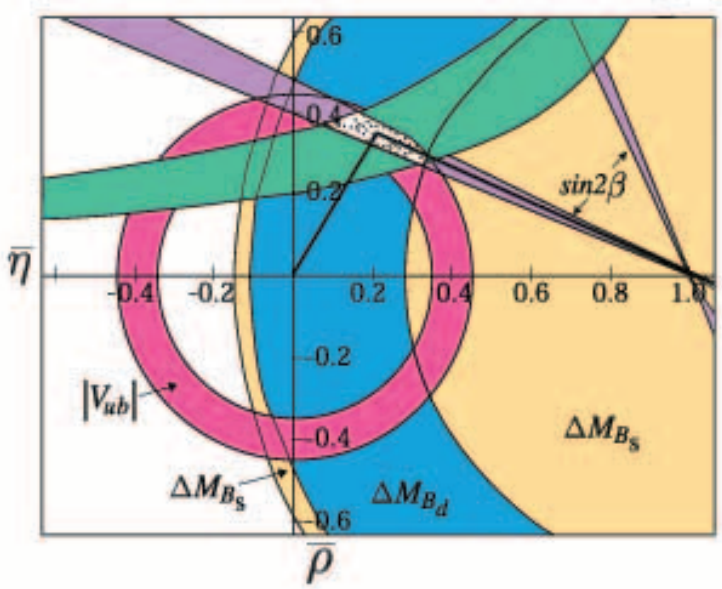


$$V_{KM} \equiv \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

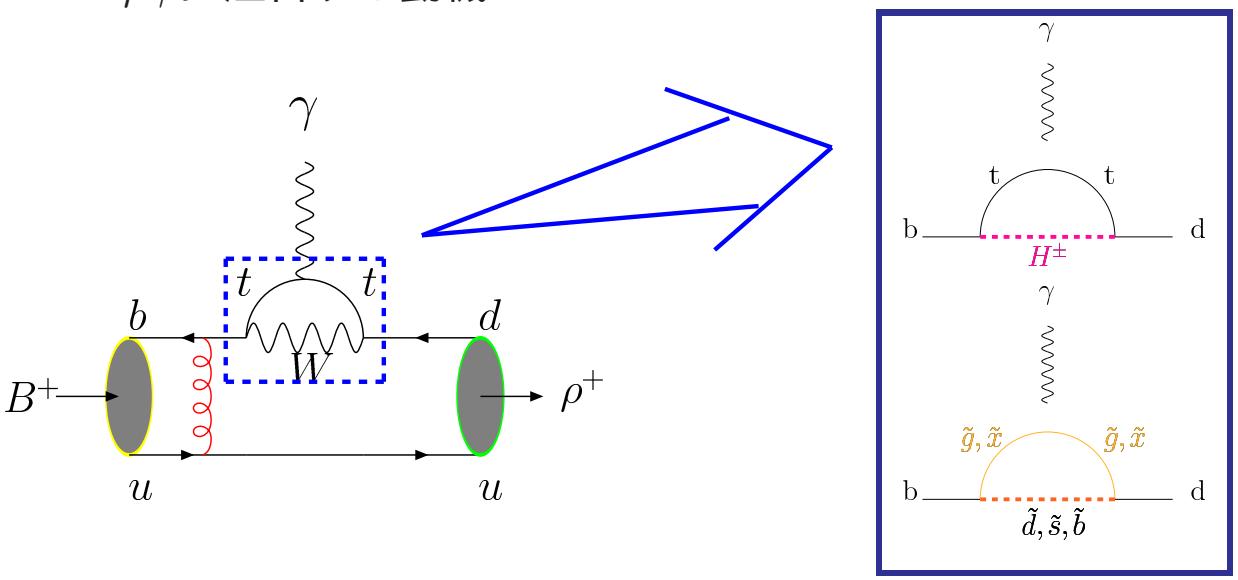
$$(A = 0.82,\ \lambda = 0.22,\ \bar{\rho} = 0.20 \pm 0.09,\ \bar{\eta} = 0.33 \pm 0.05)$$

$$A_{CP}(t) = \frac{Br(B(t) \to f) - Br(\bar{B}(t) \to f)}{Br(B(t) \to f) + Br(\bar{B}(t) \to f)} = -S \sin(\Delta M_B t) + C \cos(\Delta M_B t)$$

- ϕ_1 : $B \to J/\psi K_s$ $\quad S = \sin 2\phi_1 = 0.736 \pm 0.049$ $\quad (\phi_1 = 23.4^\circ \pm 2^\circ)$
- ϕ_2 : $B^0 \to \pi^+\pi^0$ $\quad S = \sin 2\phi_2 = -0.47 \pm 0.26$ $\quad (78^\circ < \phi_2 < 152^\circ)$

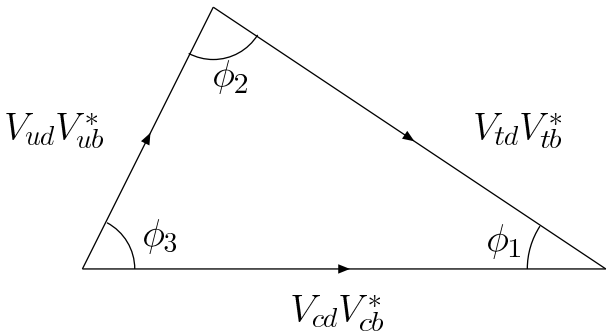


< $B \to \rho\gamma$ に注目する動機 >



Flavor-Changing-Neutral-Current $\Longrightarrow$ New Physics の検出に期待

- Radiative $b \to d\gamma$ decay の証拠 $\Longrightarrow$ KM 行列に対する独立な解析が可能



V_{td}/V_{ts}

- ΔM_{B_d}, ΔM_{B_s}
- inclusive ratio $Br(B \to X_d\gamma)/Br(B \to X_s\gamma)$
- exclusive ratio $Br(B \to \rho\gamma)/Br(B \to K^*\gamma)$

$<\Delta M_{B_d}, \Delta M_{B_s}>$

$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \frac{M_{B_s}}{M_{B_d}} \frac{\hat{B}_{B_s} f_{B_s}^2}{\hat{B}_{B_d} f_{B_d}^2} \frac{|V_{tb}^* \cdot V_{ts}|^2}{|V_{tb}^* \cdot V_{td}|^2}$$

$$\frac{\hat{B}_{B_s} f_{B_s}^2}{\hat{B}_{B_d} f_{B_d}^2} = (1.15 \pm 0.06^{+0.07}_{-0.00})^2 \implies \frac{|V_{td}|}{|V_{ts}|} < 0.25$$

(Andreas S, Kronfeld, AIP Conf.Proc.618:459-469,2002, Phys.Rev.D66, 010001-1)

< Inclusive $b \to d\gamma$ decay>

$$0.017 \leq \frac{Br(B \to X_d \gamma)}{Br(B \to X_s \gamma)} \leq 0.074$$

(A.Ali, H.Asatrian, C.Greub Phys.Lett.B429:87-98,1998)

< Exclusive $b \to d\gamma$ decay>

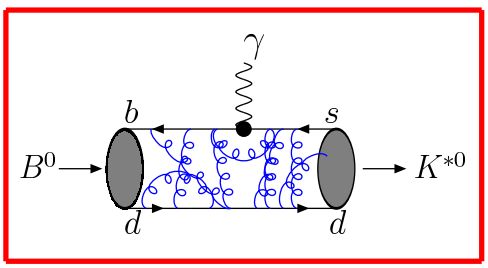
	$Br(B^+ \to \rho^+ \gamma)$	$Br(B^0 \to \rho^0 \gamma)$	$Br(B^0 \to \omega \gamma)$
Belle	$(1.8^{+0.8}_{-0.7} \pm 0.1) \times 10^{-6}$	$(0.5^{+0.5}_{-0.4} \pm 0.2) \times 10^{-6}$	$(1.3^{+0.7}_{-0.6}) \times 10^{-6}$
BaBar	$< 2.3 \times 10^{-6}$	$< 1.5 \times 10^{-6}$	$< 1.2 \times 10^{-6}$

$$\frac{Br(B \to \rho\gamma)}{Br(B \to K^*\gamma)} \simeq \frac{|V_{td}|^2}{|V_{ts}|^2} \frac{F_\rho^2}{F_{K^*}^2} = (4.2 \pm 1.3) \times 10^{-2} \quad \text{(Belle) hep-ex/0406059}$$

$$< 0.047 \quad \text{(BaBar) hep-ex/0207073}$$

Direct CP asymmetry : $A_{cp} = \dfrac{\Gamma(\bar{B} \to \bar{\rho}\gamma) - \Gamma(B \to \rho\gamma)}{\Gamma(\bar{B} \to \bar{\rho}\gamma) + \Gamma(B \to \rho\gamma)}$

Isospin breaking : $\Delta^{\pm 0} = \dfrac{\Gamma(B^\pm \to \rho^\pm \gamma)}{2\Gamma(B^0(\bar{B}^0) \to \rho^0 \gamma)} - 1$

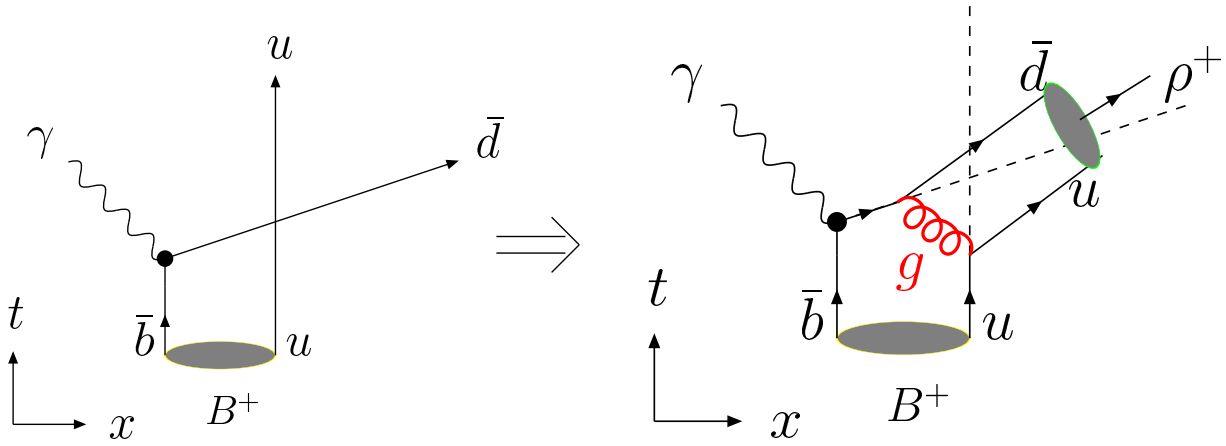


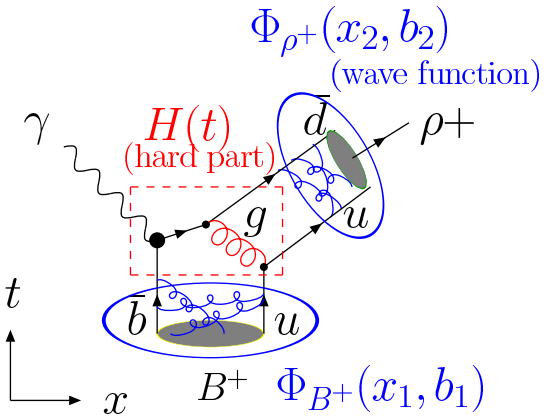
Approach

Lattice gauge theory, QCD sum rule, QCD Factorization, pQCD, ...

2. PQCDの簡単なReview

静止した B^+ 中間子が ρ^+ と γ に崩壊





H : hard part(Perturbative)

Φ_B, Φ_ρ : 波動関数 (non-Perturbative)

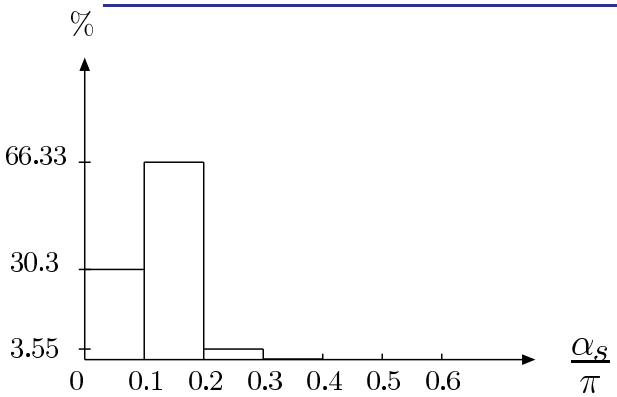
$\exp[-S(t)]$: Sudakov factor

$t = t(x_1, x_2)$: fatorization scale

$$\text{Amp} = \int \Phi_B(x_1, b_1) \otimes H(t) \otimes \Phi_\rho(x_2, b_2) \otimes \exp[-S(t)]$$

(H.N.Li, G.Sterman Nucl.Phys.B381:129-140,1992)

<グルオンの各エネルギー領域が、全崩壊振幅に寄与する割合>



$\alpha_s/\pi \leq 0.2$ からの寄与 $\Longrightarrow$ 96%

$\Downarrow$

確かに摂動的に扱えることを確認！

- ρ meson $\Longleftarrow$ Light-cone QCD sume rules

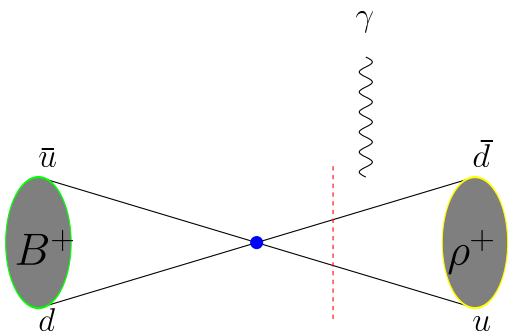
(P.Ball, V.M.Braun, Y.Koike, K.Tanaka Nucl.Phys.B529:323-382,1998)

- B meson $\Longleftarrow$ Model function

$$\Phi_B \sim (\not{P} + M_B)\gamma^5 x^2(1-x)^2 \exp\left[-\frac{1}{2}\left(\frac{xM_B}{\omega_B}\right)^2 - \frac{\omega_B^2 b^2}{2}\right] \quad (\omega_B = 0.36 \sim 0.44)$$

(M.Bauer, M.Wirbel Z.Phys.C42:671,1989)

pQCDの特徴 : Annihilation の寄与を計算可能



< CP Asymmetry >

$$A(B \to f) = Ae^{i\delta_a}e^{i\theta_a} + Be^{i\delta_b}e^{i\theta_b}, \qquad \bar{A}(\bar{B} \to \bar{f}) = Ae^{i\delta_a}e^{-i\theta_a} + Be^{i\delta_b}e^{-i\theta_b}$$

$$\text{Asy} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \propto \sin(\delta_a - \delta_b)\sin(\theta_a - \theta_b)$$

Strong-Phase が求まる

$\Downarrow$

CP Asymmetry の解析、標準模型の検証

3. pQCDによる $B \to \rho\gamma$ 崩壊の解析

< $B \to \rho\gamma$ 崩壊に寄与するoperator >

$$H_{\rm eff}(B \to d\gamma) = -\frac{G_F}{\sqrt{2}} \sum_{i=1}^{8} V_{KM} C_i(\mu) O_i(\mu)$$

- current-current operator

$$O_1^u = (\bar{d}_i u_j)_{V-A}(\bar{u}_j b_i)_{V-A} \qquad O_1^c = (\bar{d}_i c_j)_{V-A}(\bar{c}_j b_i)_{V-A}$$
$$O_2^u = (\bar{d}_i u_i)_{V-A}(\bar{u}_j b_j)_{V-A} \qquad O_2^c = (\bar{d}_i c_i)_{V-A}(\bar{c}_j b_j)_{V-A}$$

- QCD-penguin operator

$$O_3 = (\bar{d}_i b_i)_{V-A} \sum_q (\bar{q}_j q_j)_{V-A}$$
$$O_4 = (\bar{d}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$
$$O_5 = (\bar{d}_i b_i)_{V-A} \sum_q (\bar{q}_j q_j)_{V+A}$$
$$O_6 = (\bar{d}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}$$

- electro-magnatic penguin operator

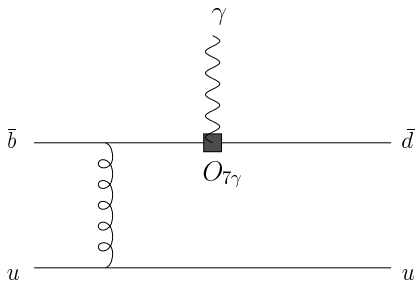
$$O_{7\gamma} = \frac{e}{4\pi^2} \bar{d}_i \sigma^{\mu\nu} (m_d P_L + m_b P_R) b_i F_{\mu\nu}$$

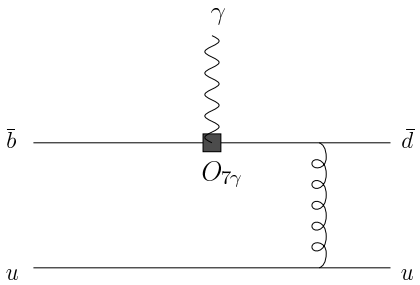
- chromo magnetic penguin operator

$$O_{8g} = \frac{g}{4\pi^2} \bar{d}_i \sigma^{\mu\nu} (m_d P_L + m_b P_R) T^a_{ij} b_j G^a_{\mu\nu}$$

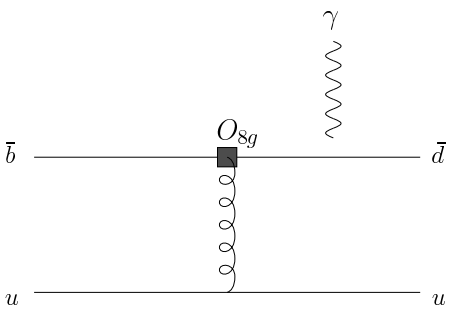
$$\left(P_L = \frac{1-\gamma^5}{2}, \qquad P_R = \frac{1+\gamma^5}{2} \right)$$

$O_{7\gamma}$ Electro-Magnetic-Penguin

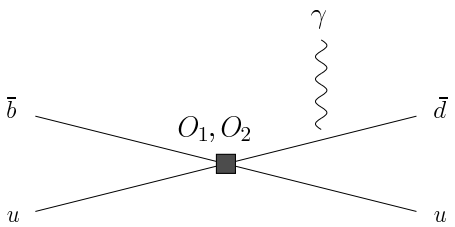




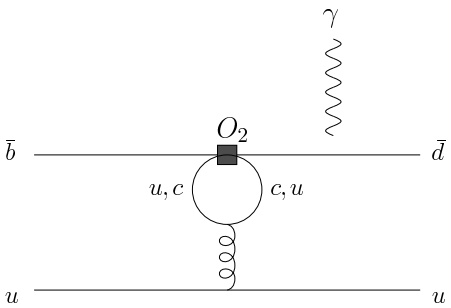
O_{8g} Chromo-Magnetic-Penguin

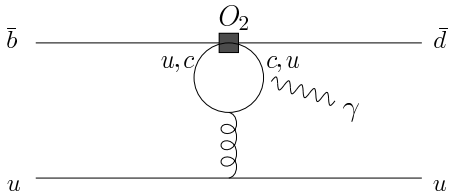


O_1, O_2 Annihilation

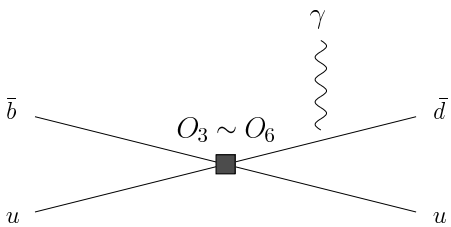


O_2 Charm-Penguin, Up-Penguin

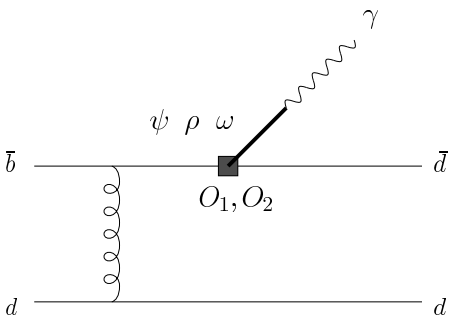




$O_3 \sim O_6$ QCD-Penguin

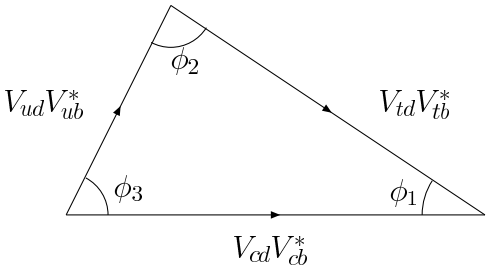


O_1, O_2 Long-Distance



4. 考察

1. Branching ratio



$$V_{KM} \equiv \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$(A = 0.82,\ \lambda = 0.22,\ \bar{\rho} = 0.20 \pm 0.09,\ \bar{\eta} = 0.33 \pm 0.05)$$

$$\begin{aligned} Br(B^\pm \to \rho^\pm\gamma) &= (1.18^{+0.74}_{-0.30}) \times 10^{-6} \\ Br(B^0 \to \rho^0\gamma) &= (0.65^{+0.22}_{-0.30}) \times 10^{-6} \\ Br(B^0 \to \omega\gamma) &= (0.66^{+0.22}_{-0.30}) \times 10^{-6} \end{aligned}$$

< 実験値 >

	$Br(B^+ \to \rho^+\gamma)$	$Br(B^0 \to \rho^0\gamma)$	$Br(B^0 \to \omega\gamma)$
Belle	$(1.8^{+0.8}_{-0.7} \pm 0.1) \times 10^{-6}$	$(0.5^{+0.5}_{-0.4} \pm 0.2) \times 10^{-6}$	$(1.3^{+0.7}_{-0.6}) \times 10^{-6}$
BaBar	$< 2.3 \times 10^{-6}$	$< 1.5 \times 10^{-6}$	$< 1.2 \times 10^{-6}$

$$Br(B \to (\rho,\omega)\ \gamma) = (1.38 \pm 0.42) \times 10^{-6}$$

(A.Ali, A.Y.Parkhomeuko hep-ph/0405075)

$$Br(B^\pm \to \rho^\pm\gamma) = (1.6^{+0.7}_{-0.5}) \times 10^{-6},\ \ Br(\bar{B}^0 \to \rho^0\gamma) = (0.8^{+0.4}_{-0.3}) \times 10^{-6}$$

(S.W.Bosch hep-oh/0208203)

$$\begin{aligned} Br(B^\pm \to \rho^\pm\gamma) &= (0.90 \pm 0.33 \pm 0.10) \times 10^{-6} \\ Br(\bar{B}^0 \to \rho^0\gamma) &= (0.49 \pm 0.18 \pm 0.04) \times 10^{-6} \end{aligned}$$

(A.Ali, A.Y.Parkhomeuko Eur.Phys.J.C23:89-112,2002)

$$Br(B^\pm \to \rho^\pm\gamma) = (1.9 \pm 1.6) \times 10^{-6},\qquad Br(\bar{B}^0 \to \rho^0\gamma) = (0.85 \pm 0.65) \times 10^{-6}$$

(A.Ali, V.M.Braun, Phys.Lett.B359:223-235,1995)

2. $|V_{td}|/|V_{ts}|$

$$\mathcal{R}(d\gamma/s\gamma) \equiv \frac{Br(B \to \rho\gamma)}{Br(B \to K^*\gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2}\frac{F_\rho^2}{F_{K^*}^2}(1+\Delta S)$$

Form factor

$$\langle V(k,\eta)\gamma(q,\epsilon) \mid O_{7\gamma} \mid B\rangle = -\frac{e}{2\pi^2} m_b F_V [\epsilon^{\mu\nu\lambda\rho}\epsilon_\mu \eta_\nu k_\lambda q_\rho + i\{(\epsilon\cdot\eta)(k\cdot q) - (\epsilon\cdot k)(\eta\cdot q)\}]$$

$F_{K^*} = 0.27^{+0.05}_{-0.03}$, $F_\rho = 0.29^{+0.04}_{-0.04}$, $\Delta S = (-7.3^{+2.8}_{-3.4}) \times 10^{-2}$

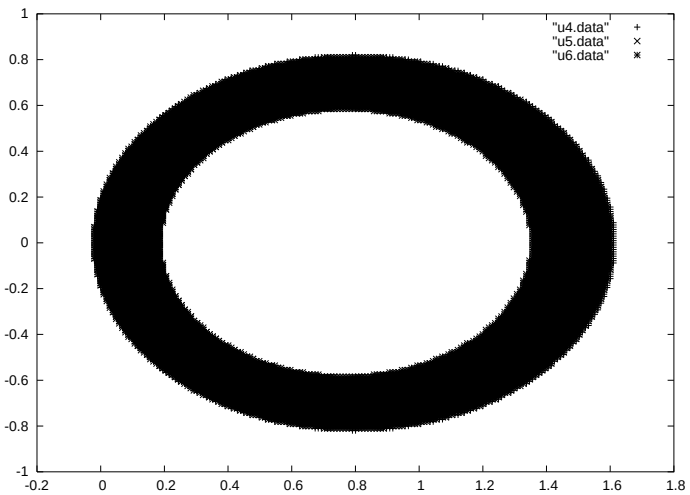
(hep-ph/0406055 Y.Y.Keum, M.Matsumori, A.I.Sanda)

$$\Downarrow$$

$$\mathcal{R}_{th}(d\gamma/s\gamma) = (3.6^{+1.7}_{-1.1}) \times 10^{-2}$$

$\mathcal{R}_{exp}(d\gamma/s\gamma) = (4.2 \pm 1.3) \times 10^2$ (Belle) hep-ex/0406059

$\mathcal{R}_{exp}(d\gamma/s\gamma) < 0.047$ (BaBar) hep-ex/0207073



$$\Downarrow$$

$$0.12 \leq \frac{|V_{td}|}{|V_{ts}|} \leq 0.22$$

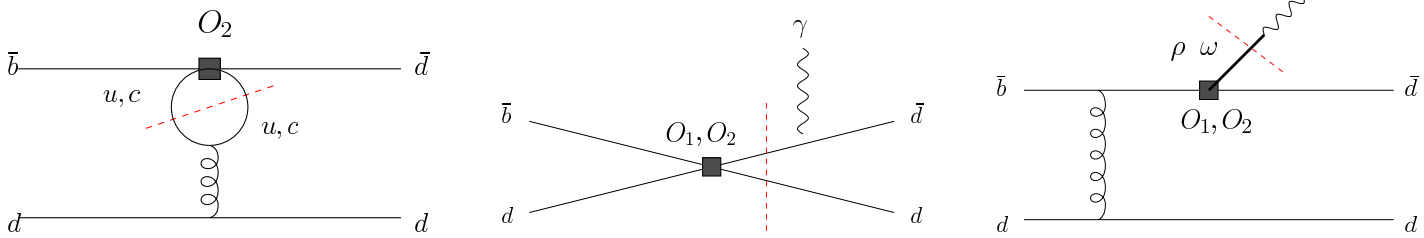
$$\frac{|V_{td}|}{|V_{ts}|} < 0.25 \qquad (\Delta M_{B_d}, \Delta M_{B_s}) \qquad \text{(Phys.Rev.D66, 010001-1)}$$

$$0.13 \leq \frac{|V_{td}|}{|V_{ts}|} \leq 0.27 \qquad \text{(Inclusive decay)} \qquad \text{(Ali,Asatrian,Greub PLB429:87-98,1998)}$$

$$0.16 \leq \frac{|V_{td}|}{|V_{ts}|} \leq 0.29 \qquad \text{(Exclusive decay)} \qquad \text{(Ali, Lunghi, Parkhomenko hep-ph/0405075)}$$

3. Direct CP asymmetry

$O_{7\gamma}$ とloop contribution, O_2 Annihilation, Long-distanceの干渉



$$A_{cp}(\rho^0\gamma) = \frac{\Gamma(\bar{B}^0 \to \rho^0\gamma) - \Gamma(B^0 \to \rho^0\gamma)}{\Gamma(\bar{B}^0 \to \rho^0\gamma) + \Gamma(B^0 \to \rho^0\gamma)} = (-8.2^{+3.5}_{-2.6}) \times 10^{-2}$$

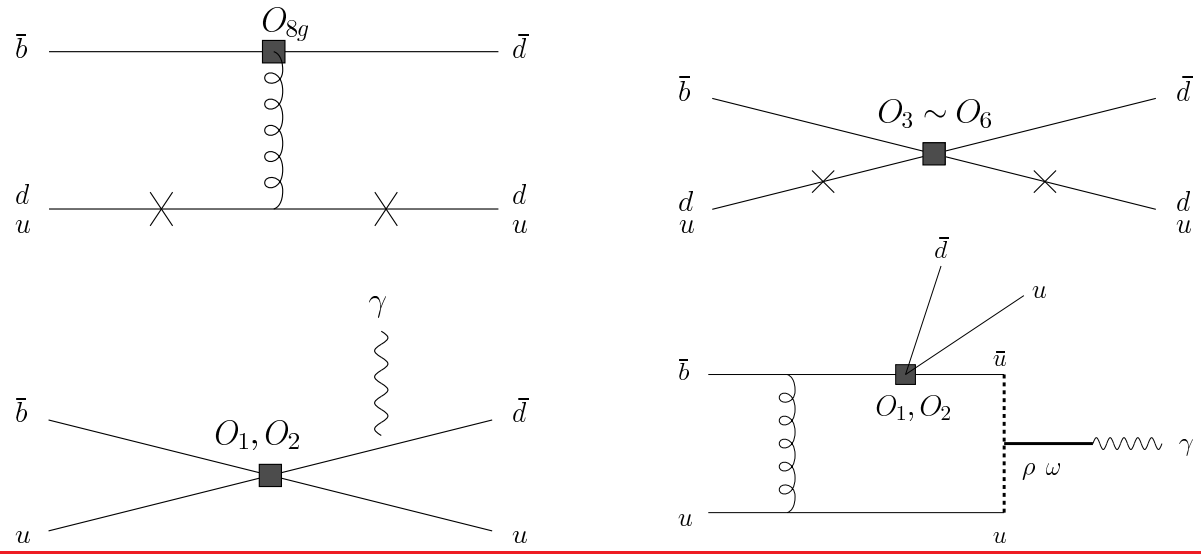
$$A_{cp}(\rho^\pm\gamma) = \frac{\Gamma(B^- \to \rho^-\gamma) - \Gamma(B^+ \to \rho^+\gamma)}{\Gamma(B^- \to \rho^-\gamma) + \Gamma(B^+ \to \rho^+\gamma)} = (-9.6^{+3.7}_{-3.0}) \times 10^{-2}$$

$A_{cp}((\rho,\omega)\gamma) \simeq -0.1$ (A.Ali, E.Lunghi, A.Y.Parkhomenko hep-ph/0405075)

$A_{cp}(\rho^0\gamma) = -0.06 \pm 0.02, \quad A_{cp}(\rho^\pm\gamma) = 0.10^{+0.03}_{-0.02}$

(A.Ali, E.Lunghi Eur.Phys.J.C26:195-200,2002)

4. Isospin breaking

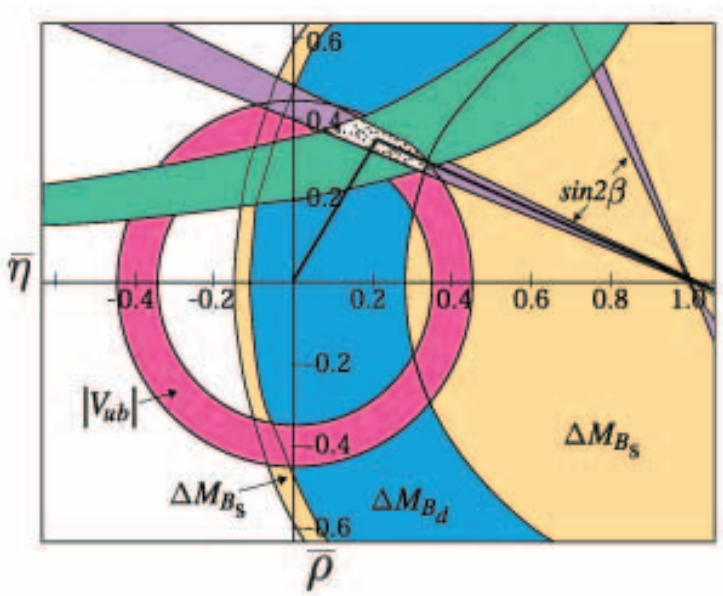


$$\Delta_{+0} = \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1, \qquad \Delta_{-0} = \frac{\Gamma(B^- \to \rho^-\gamma)}{2\Gamma(\bar{B}^0 \to \rho^0\gamma)} - 1$$

$$\Delta(\rho\gamma) = \frac{\Delta_{+0} + \Delta_{-0}}{2} = -(16.8^{+6.5}_{-6.2}) \times 10^{-2}$$

$\Delta(\rho\gamma) = (1.1 \pm 3.9) \times 10^{-2}$ (A.Ali, E.Lunghi, A.Y.Parkhomenko, hep-ph/0405075)

$\Delta(\rho\gamma) = 0.04^{+0.14}_{-0.07}$ (A.Ali, E.Lunghi Eur.Phys.J.C26:195-200,2002)

$|\Delta(\rho\gamma)| \leq 10\%$ (A.Ali, A.Y.Parkhomenko Eur.Phys.J.C23:89-112,2002)

< $\bar{\rho} - \bar{\eta}$ plain >