Verifying the Standard Model for Exploring New Physics in $B \to K^* \gamma$ decay mode with pQCD

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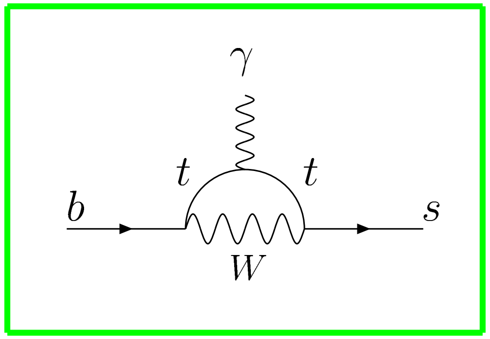
Br-ratio, direct CP Asy, Isospin breaking within the Standard Model
Possibility for exploring New Physics beyond the Standard Model

1. Introduction
2. Review of pQCD
3. Analysis of $B \to K^* \gamma$ decay mode with pQCD
4. Summary

1. Introduction

< Verify the Standard Model, Explore the New Physics >



FCNC $\Longrightarrow$ Expectation for seaching

	BaBar(10^{-5}) Phy.Rev.Lett 88,10	Belle(10^{-5}) Belle-Conf-0319
$\mathrm{Br}(B^{\pm} \to K^{*\pm}\gamma)$	$3.83 \pm 0.62 \pm 0.22$	$4.40 \pm 0.33 \pm 0.21$
$\mathrm{Br}(B^{0} \to K^{*0}\gamma)$	$4.23 \pm 0.40 \pm 0.22$	$4.09 \pm 0.21 \pm 0.19$
A_{CP}	$-0.044 \pm 0.076 \pm 0.012$	$-0.001 \pm 0.044 \pm 0.008$

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

$$\mathrm{Asy} = \frac{\Gamma(\bar{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\bar{B} \to f) + \Gamma(B \to \bar{f})} \simeq \frac{B}{A}\sin(\delta_a - \delta_b)\sin(\theta_a - \theta_b) \qquad (|A| >> |B|)$$

Large Br-ratio $\Longrightarrow$ Exp. error of CP Asy is about several %

Theoretical prediction for direct CP Asy is small ($O_{7\gamma}$ is dominant)

$\Updownarrow$

How small is the CP Asy within the SM ?

$\Downarrow$

This is very impotant for NP search !

< Inclusive $b \longrightarrow s\gamma$ decay>

Inclusive $b \longrightarrow s\gamma$ can be easily estimated.

$$\boxed{\begin{array}{l} Br(B \rightarrow X_s\gamma)^{exp} = (3.23 \pm 0.42) \times 10^{-4} \\ Br(B \rightarrow X_s\gamma)^{th} = (3.57 \pm 0.30) \times 10^{-4} \end{array}}$$

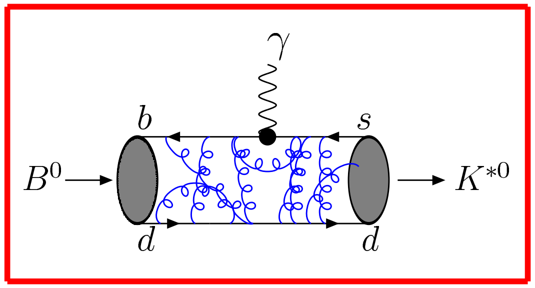
(world average)

(Buras,Czarnecki,Misiak,Urban Nucl.Phys.B631)

Good agreement between experiment and theory !

< Exclusive $b \longrightarrow s\gamma$ decay>

Dificulty for treating hadronic matrix element



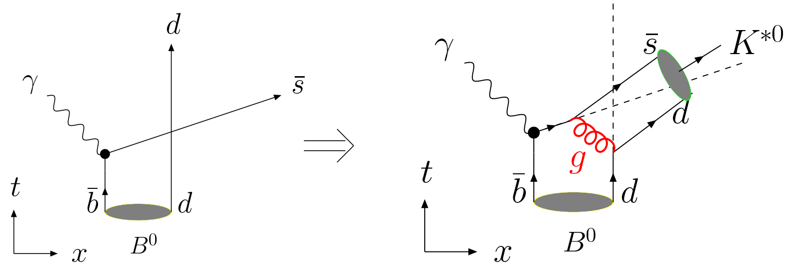
< Approach >

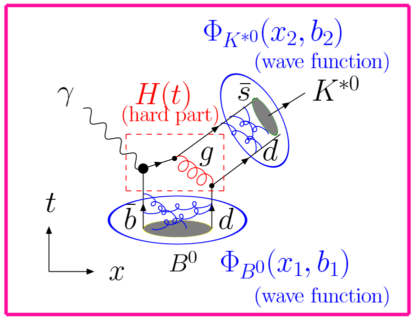
Lattice gauge theory, QCD sum rule, QCD Factorization, pQCD, ...

2. Review of pQCD

Botts,Sterman NPB 325,62,1989

The rest B^0 meson decays into K^{*0} meson and γ





H : hard part(Perturbative)

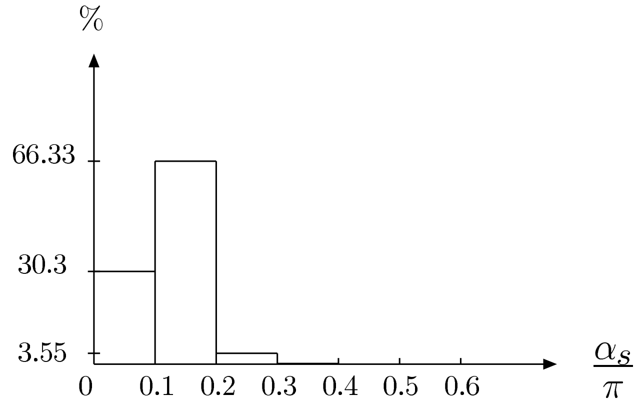
Φ_B, Φ_{K^*} : wave function(non-Perturbative)

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

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

$$\mathrm{Amp} = \int \Phi_B(x_1, b_1) \otimes H(t) \otimes \Phi_{K^*}(x_2, b_2) \otimes \exp\left[-S(t)\right]$$

The contribution for the total decay amplitude



contribution from $\alpha_s/\pi \leq 0.2 \implies 96\%$

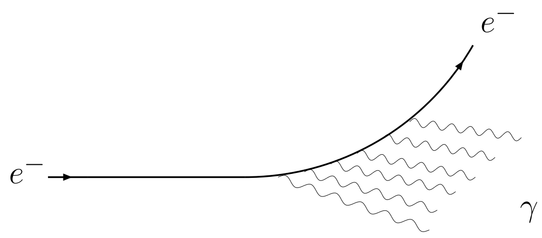
$\Downarrow$

Perturbative !

Sudakov factor postulates that the soft contributions to the form factor are strongly suppressed.

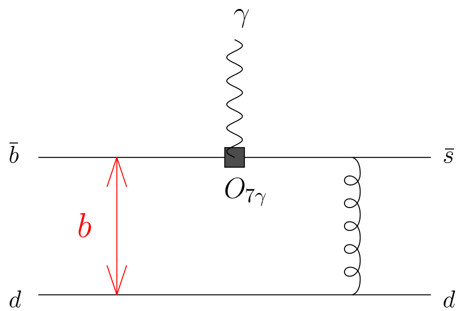
< Physical meaning of Sudakov factor >

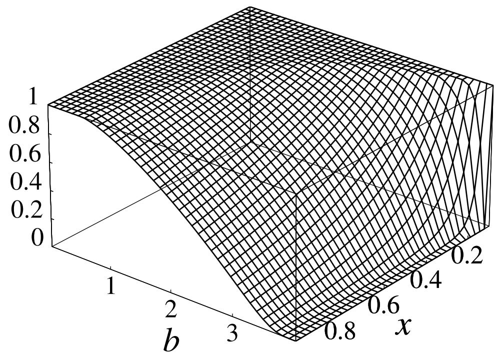
- QED



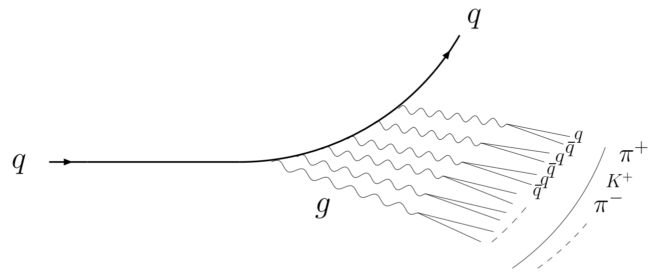
Rapid acceleration of charged particle

$\Longrightarrow$ infinitely many photons are emitted by bremsstrahlung





- QCD



Rapid acceleration of quark

$\Longrightarrow$ infinitely many gluons are emitted by bremsstrahlung

$\Longrightarrow$ many hadrons are formed

What conditions are needed ?

Emitted gluons should be reabsorbed before hadron formation

$\Downarrow$

Transverse interval between partons b should be small !

(If b is large, amplitude for emitting no gluon is suppressed.)

$\Longrightarrow$ small $k_\perp$ region is suppressed

Sudakov factor gives the probability for emitting no soft gluon.

(pQCD approach is phenomenologically justified)

3. Analysis of $B \longrightarrow K^*\gamma$ decay mode with PQCD

< Operators for $B \to K^*\gamma$ decay >

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

- current-current operator

$$\begin{aligned} O_1 &= (\bar{s}_i c_j)_{V-A}(\bar{c}_j b_i)_{V-A} \\ O_2 &= (\bar{s}_i c_i)_{V-A}(\bar{c}_j b_j)_{V-A} \end{aligned}$$

- QCD-penguin operator

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

- electro-magnatic penguin operator

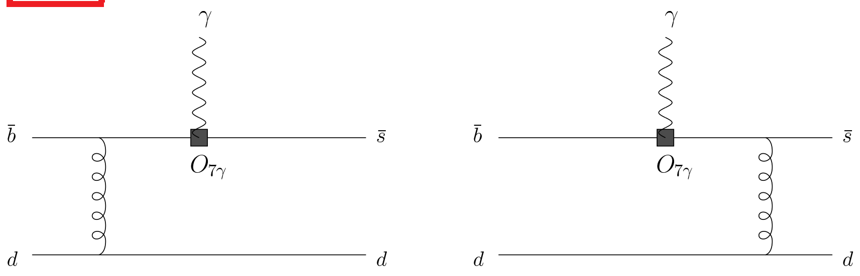
$$O_{7\gamma} = \frac{e}{4\pi^2}\bar{s}_i\sigma^{\mu\nu}(m_s P_L + m_b P_R) b_i F_{\mu\nu}$$

- chromo magnetic penguin operator

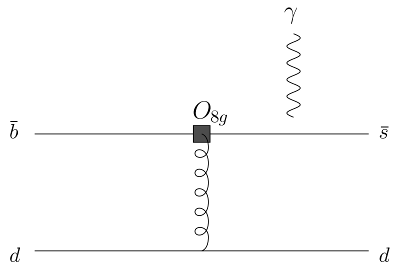
$$O_{8g} = \frac{g}{4\pi^2}\bar{s}_i\sigma^{\mu\nu}(m_s P_L + m_b P_R) T^a_{ij} b_j G^a_{\mu\nu}$$

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

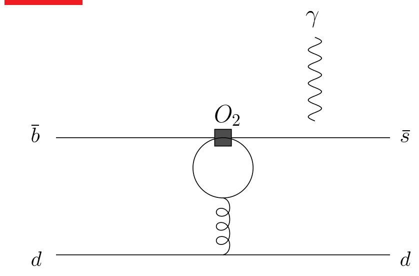
$\boxed{O_{7\gamma}}$ Electro-Magnetic-Penguin



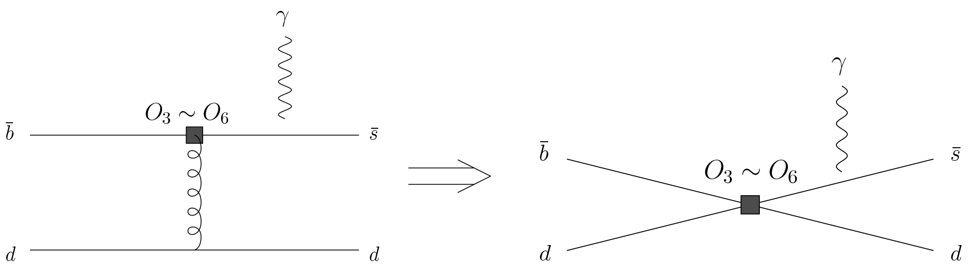
$\boxed{O_{8g}}$ Chromo-Magnetic-Penguin



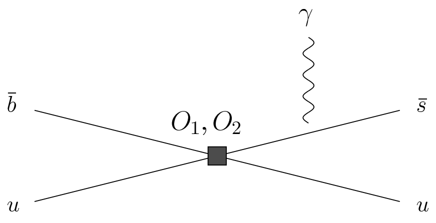
$\boxed{O_2}$ Charm-Penguin, Up-Penguin



$\boxed{O_3 \sim O_6}$ QCD-Penguin

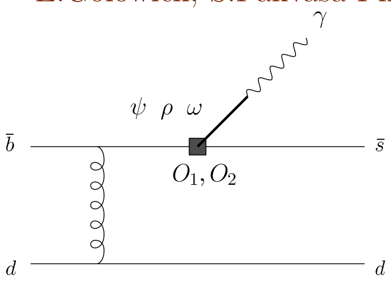


$\boxed{O_2}$ Annihilation



$\boxed{O_1, O_2}$ Long-ditance

E.Golowich, S.Pakvasa Phy.Rev.D 51,3



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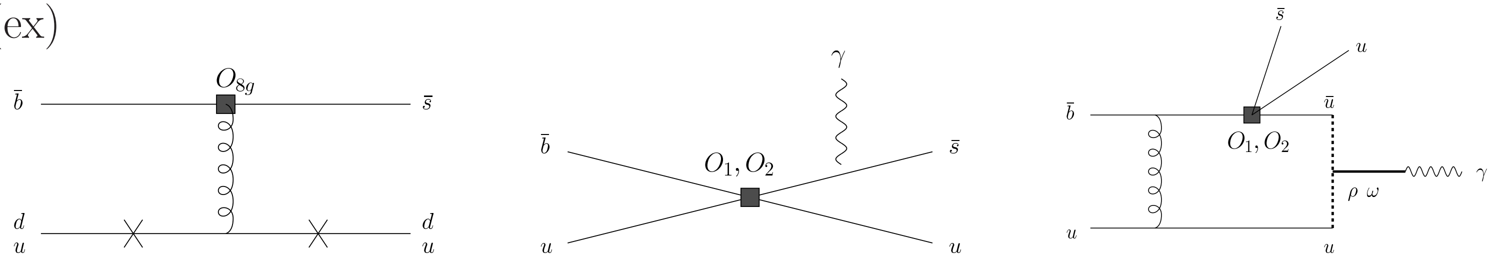
(ex)



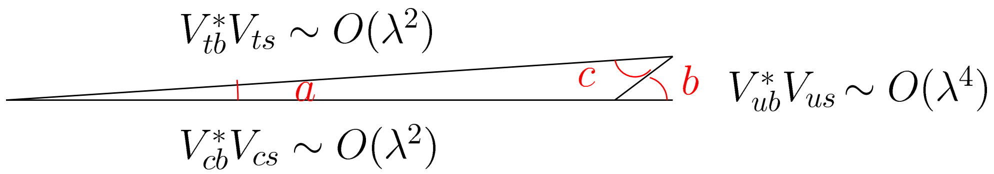
Bremsstrahlung photon emition, O_2 annihilation, long distance contribution mediated by ρ, ω

$< B^0 \to K^{*0}\gamma >$

diagram	Ope	KM	W-Phase	S-Phase	Amp
El-Mg-Pen	$O_{7\gamma}$	$V_{tb}V_{ts}^*$	0	0	$O(1)$
Chromo-Mg-Pen	O_{8g}	$V_{tb}V_{ts}^*$	0	0	$O(\lambda^3)$
Charm-Pen	O_2	$V_{cb}V_{cs}^*$	$-e^{-ia}$	$25°$	$O(\lambda^2)$
U-Pen	O_2	$V_{ub}V_{us}^*$	$-e^{ic}$	$25°$	$O(\lambda^4)$
Anni	O_2	$V_{ub}V_{us}^*$	$-e^{ic}$	0	0
QCD-Pen	$O_3 \sim O_6$	$V_{tb}V_{ts}^*$	0	$13°$	$O(\lambda^4)$
ψ	O_1, O_2	$V_{cb}V_{cs}^*$	$-e^{-ia}$	0	$O(\lambda^2)$
ρ, ω	O_1, O_2	$V_{ub}V_{us}^*$	$-e^{ic}$	$10°$	$O(\lambda^5)$

$< B^+ \to K^{*+}\gamma >$

diagram	Ope	KM	W-Phase	S-Phase	Amp
El-Mg-Pen	$O_{7\gamma}$	$V_{tb}V_{ts}^*$	0	0	$O(1)$
Chromo-Mg-Pen	O_{8g}	$V_{tb}V_{ts}^*$	0	0	$O(\lambda^3)$
Charm-Pen	O_2	$V_{cb}V_{cs}^*$	$-e^{-ia}$	$30°$	$O(\lambda^2)$
U-Pen	O_2	$V_{ub}V_{us}^*$	$-e^{ic}$	$30°$	$O(\lambda^4)$
Anni	O_2	$V_{ub}V_{us}^*$	$-e^{ic}$	$15°$	$O(\lambda^4)$
QCD-Pen	$O_3 \sim O_6$	$V_{tb}V_{ts}^*$	0	$20°$	$O(\lambda^3)$
ψ	O_2	$V_{cb}V_{cs}^*$	$-e^{-ia}$	0	$O(\lambda^2)$
ρ, ω	O_2	$V_{ub}V_{us}^*$	$-e^{ic}$	$10°$	$O(\lambda^3)$



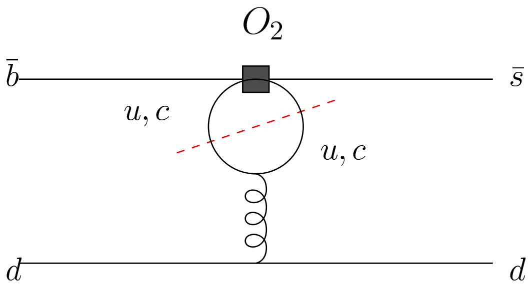
$B \to K^*\psi \to K^*\gamma$ contribution is about 5 % compared to $O_{7\gamma}$ contribution at the amplitude level.

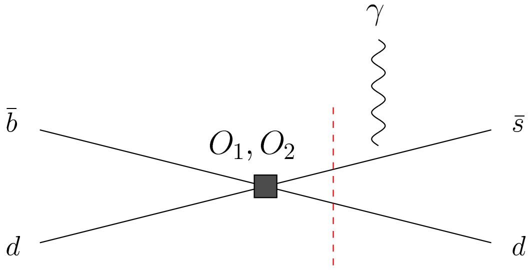
$\Longrightarrow$ Branching ratio is suppressed by 10 %.

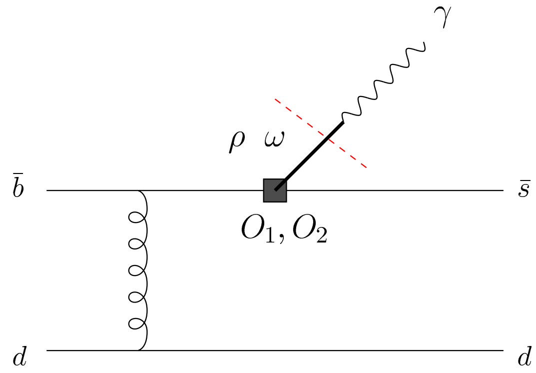
	pQCD(10^{-5})	BaBar(10^{-5})	Belle(10^{-5})
$\mathrm{Br}(B^\pm \to K^{*\pm}\gamma)$	$6.8^{+1.5}_{-1.7}$	$3.83 \pm 0.62 \pm 0.22$	$4.40 \pm 0.33 \pm 0.21$
$\mathrm{Br}(B^0 \to K^{*0}\gamma)$	$5.8^{+2.2}_{-1.1}$	$4.23 \pm 0.40 \pm 0.22$	$4.09 \pm 0.21 \pm 0.19$

< Direct CP Asy within the SM >

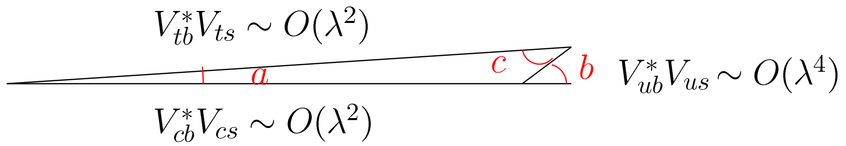
$O_{7\gamma}$ and loop contribution, O_2 Annihilation, Long-distance interference







< Unitary Triangle >



$\rho = 0.22 \pm 0.10, \eta = 0.35 \pm 0.05$

< Direct CP Asy within the SM >

- Neutral mode $B^0 \to K^{*0}\gamma$: $-(5.3^{+5.2}_{-5.8}) \times 10^{-4}$
- Charged mode $B^\pm \to K^{*\pm}\gamma$: $(0.4^{+4.5}_{-5.8}) \times 10^{-4}$

	BaBar	Belle
A_{CP}	$-0.044 \pm 0.076 \pm 0.012$	$-0.001 \pm 0.044 \pm 0.008$

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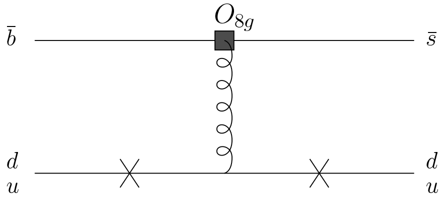
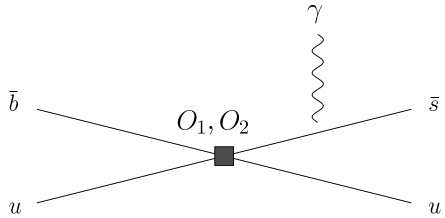
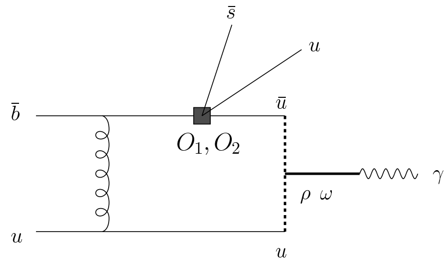
(ex)







Bremsstrahlung photon emmition,O_2 annihilation,long distance contribution mediated by ρ, ω

$$\Delta_{0+} = \frac{(\tau_{B^+}/\tau_{B^0})Br(B^0 \to K^{*0}\gamma) - Br(B^+ \to K^{*+}\gamma)}{(\tau_{B^+}/\tau_{B^0})Br(B^0 \to K^{*0}\gamma) + Br(B^+ \to K^{*+}\gamma)}$$

$$\Delta_{0+} = +0.003 \pm 0.045(\mathrm{stat}) \pm 0.018(\mathrm{syst})$$ (BELLE-CONF-0319)

$$\Delta_{0+} = 0.0^{+0.021}_{-0.040}$$

ω_B	Δ_{0+}
0.36	0.021
0.40	-0.040
0.44	0.0

4. Summary

Branching ratio

$$\mathrm{Br}(B^{\pm} \to K^{*\pm}\gamma) = (6.8^{+1.5}_{-1.7}) \times 10^{-5}, \qquad \mathrm{Br}(B^{0} \to K^{*0}\gamma) = (5.8^{+2.2}_{-1.1}) \times 10^{-5}$$

Direct CP Asymmetry

$$\mathrm{Asy}(B^{0} \to K^{*}\gamma) = -(5.3^{+5.2}_{-5.8}) \times 10^{-4}, \qquad \mathrm{Asy}(B^{\pm} \to K^{*}\gamma) = (0.4^{+4.5}_{-5.8}) \times 10^{-4}$$

Isospin breaking

$$\Delta_{0+} = 0.0^{+0.021}_{-0.040}$$

< Is it possible to verify the Standard Model or search for New Physics ?>

How many event numbers are needed to settle 1 % asymmetry ?

$$\text{Statistical Error} \propto \frac{1}{\sqrt{N}}$$

	BaBar	Belle
A_{CP}	$-0.044 \pm 0.076 \pm 0.012$	$-0.001 \pm 0.044 \pm 0.008$

(ex) Error : $4.4\% \to 1\% \Longrightarrow$ 20 times data is needed

$\Downarrow$

It may be not impossible if the Super B factory is built.

Wave Function

$$
\begin{aligned}
\langle K^*(P,\epsilon_{K^*}) \mid \bar{d}(z) I s(0) \mid 0\rangle &= \frac{1}{\sqrt{2N_c}} M_B I r_{K^*} \int_0^1 dx e^{ixP\cdot z} \phi^s_{K^*}(x) \\
\langle K^*(P,\epsilon_{K^*}) \mid \bar{d}(z) \gamma_\mu s(0) \mid 0\rangle &= \frac{1}{\sqrt{2N_c}} M_{K^*} \left[\int_0^1 dx e^{ixP\cdot z} \not\epsilon^{*L}_{K^*} \phi_{K^*}(x) + \int_0^1 dx e^{ixP\cdot z} \not\epsilon^{*T}_{K^*\mu} \phi^v_{K^*}(x) \right] \\
\langle K^*(P,\epsilon_{K^*}) \mid \bar{d}(z) \gamma_\mu \gamma^5 s(0) \mid 0\rangle &= \frac{i}{\sqrt{2N_c}} \frac{M_{K^*}}{(P\cdot n^-)} \epsilon_{\mu\nu\alpha\beta} \left[\gamma^\mu \gamma^5\right] \epsilon^{*T}_{K^*\nu} p_\alpha n^-_\beta \int_0^1 dx e^{ixP\cdot z} \phi^a_{K^*}(x) \\
\langle K^*(P,\epsilon_{K^*}) \mid \bar{d}(z) \sigma_{\mu\nu} s(0) \mid 0\rangle &= \frac{1}{\sqrt{2N_c}} \left[\not\epsilon^{*T}_{K^*} \not P \int_0^1 dx e^{ixP\cdot z} \phi^T_{K^*}(x) + \not\epsilon^{*L}_{K^*} \not P \int_0^1 dx e^{ixP\cdot z} \phi^t_{K^*}(x) \right]
\end{aligned}
$$

$$
\begin{aligned}
\Phi^L_{K^*} &= \frac{1}{\sqrt{2N_c}} \int_0^1 dx e^{ixP\cdot z} \{ M_{K^*} [\not\epsilon^{*L}_{K^*}] \phi_{K^*}(x) + [\not\epsilon^{*L}_{K^*} \not P] \phi^t_{K^*}(x) + M_{K^*} [I] \phi^s_{K^*}(x) \} \\
\Phi^T_{K^*} &= \frac{1}{\sqrt{2N_c}} \int_0^1 dx e^{ixP\cdot z} \{ M_{K^*} [\not\epsilon^{*T}_{K^*}] \phi^v_{K^*}(x) + [\not\epsilon^{*T}_{K^*} \not P] \phi^T_{K^*}(x) + \frac{M_{K^*}}{P_2\cdot n_+} i\epsilon_{\mu\nu\rho\sigma} [\gamma^\mu \gamma^5] \epsilon^{T\nu}_{K^*} P^\rho_2 n^\sigma_+ \phi^a_{K^*}(x) \} \\
\Phi_B &= (\not P_1 + M_B)\gamma^5 \phi_B(x_1) \qquad \phi_B(x) = N_B x^2 (1-x)^2 \, e^{-\frac{1}{2}\left(\frac{xM_B}{\omega_B}\right)^2 - \frac{b^2\omega_B^2}{2}}
\end{aligned}
$$

$$(\omega_B : 0.4 \pm 0.04)$$

	$B^0 \to K^{*0}\gamma$			$B^\pm \to K^{*\pm}\gamma$	
	$M^S(10^{-6})$	$M^P(10^{-6})$		$M^S(10^{-6})$	$M^P(10^{-6})$
$O_{7\gamma}$	-260.47	260.47		-260.47	260.47
O_{8g}	-3.62-0.01i	3.66+0.05i		-3.44-0.13i	3.36+0.05i
Cha-Pen	11.21+5.97i	-16.56-6.96i		6.56-3.6i	1.58+5.17i
QCD Pen	1.35+0.31i	-0.97-0.03i		-4.8-1.59i	4.14+1.02i
ψ	13.54	-13.54		13.54	-13.54