An Analysis of Supersymmetric Effects on $B \to \phi K$ Decays in the PQCD Approach

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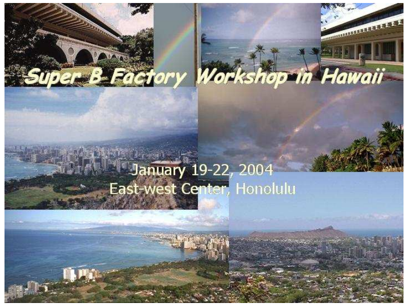
S. M. and A. I. Sanda, accepted in PRD. [hep-ph/0311068]

S. M. and A. I. Sanda, Prog. Theor. Phys. 110 (2003) 549 [hep-ph/0305073]

Super B Factory Workshop in Hawaii, Jan. 21, 2004



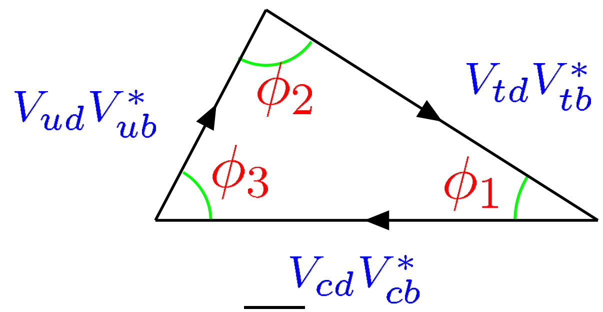
Outline

1. Introduction
2. Perturbative QCD Approach in Exclusive B Decays
   - Review of PQCD
3. MSSM Contribution in B Decays
   - Mass Insertion Approximation
   - Constraint from $\mathrm{Br}(B \to X_s \gamma)$
4. MSSM Effects on $B \to \phi K$ Decays
   - Branching Ratio and CP Asymmetry for $B_d \to \phi K_S$ and $B^{\pm} \to \phi K^{\pm}$
5. Summary

1. Introduction

The time-dependent CP asymmetry

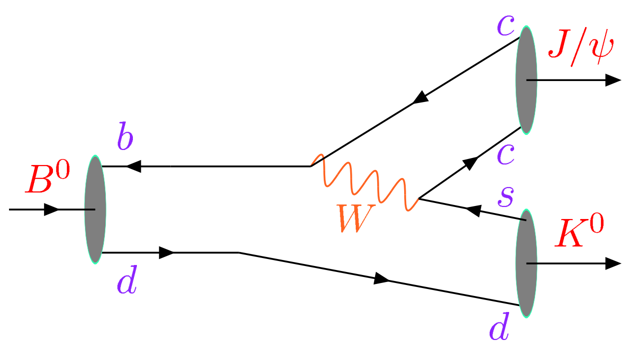
$$a_{f_{CP}}(t) \equiv \frac{\Gamma(\overline{B^0}(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B^0}(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} \equiv A_{f_{CP}} \cos(\Delta M_B t) + S_{f_{CP}} \sin(\Delta M_B t)$$



$$A_{f_{CP}} \equiv \frac{|\lambda_{f_{CP}}|^2 - 1}{|\lambda_{f_{CP}}|^2 + 1}, \quad S_{f_{CP}} \equiv \frac{2\mathrm{Im}\lambda_{f_{CP}}}{|\lambda_{f_{CP}}|^2 + 1}, \quad \lambda_{f_{CP}} = e^{-2i\,\phi_1} \frac{\mathcal{A}(\overline{B^0} \to f_{CP})}{\mathcal{A}(B^0 \to f_{CP})}$$

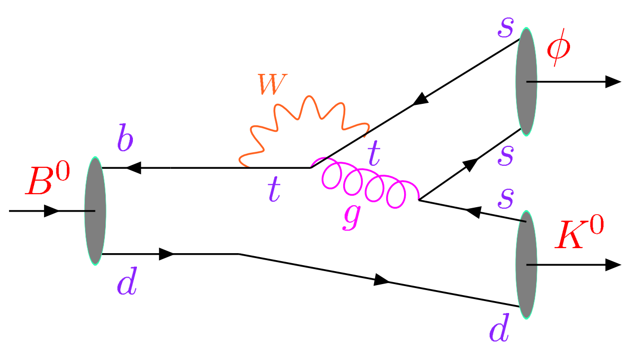
- $B^0 \to J/\psi K_S$: Tree dominant, $\mathcal{A}_{J/\psi K_S} = V_{cb}^* V_{cs} A_1$

  $\Longrightarrow \quad S_{J/\psi K_S} = \sin(2\phi_1), \; A_{J/\psi K_S} = 0$



- $B^0 \to \phi K_S$: Pure penguin, $\mathcal{A}_{\phi K_S} = V_{tb}^* V_{ts} A_2$

  $\Longrightarrow \quad S_{\phi K_S} = \sin(2\phi_1), \; A_{\phi K_S} = 0$



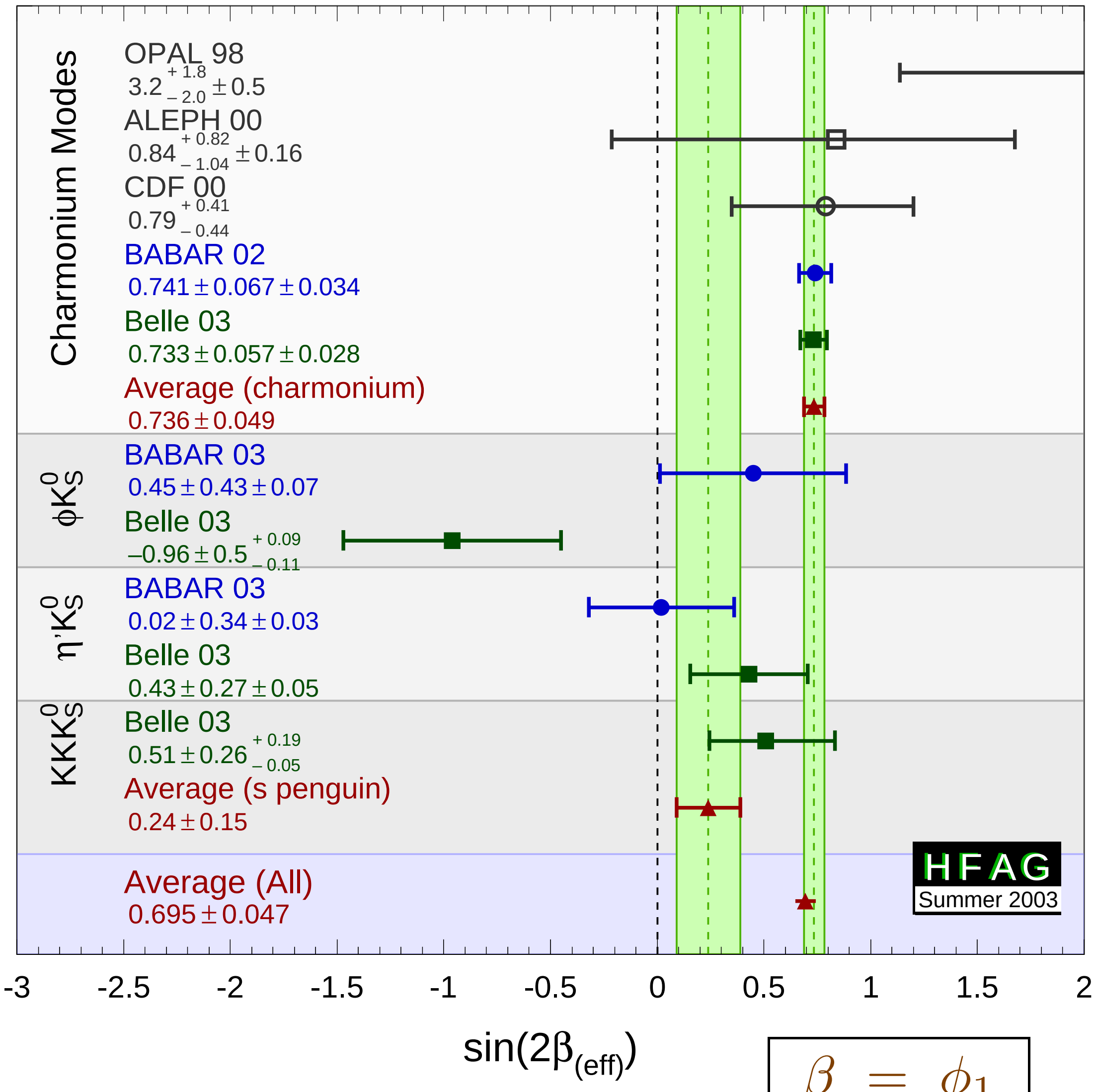
$$|S_{J/\psi K_S} - S_{\phi K_S}| \gg \mathcal{O}(\lambda^2)$$

$\Longrightarrow$ New Physics in ϕK_S

$$\lambda = \sin\theta_c \simeq 0.22$$

Experimental Results

http://www.slac.stanford.edu/xorg/hfag/



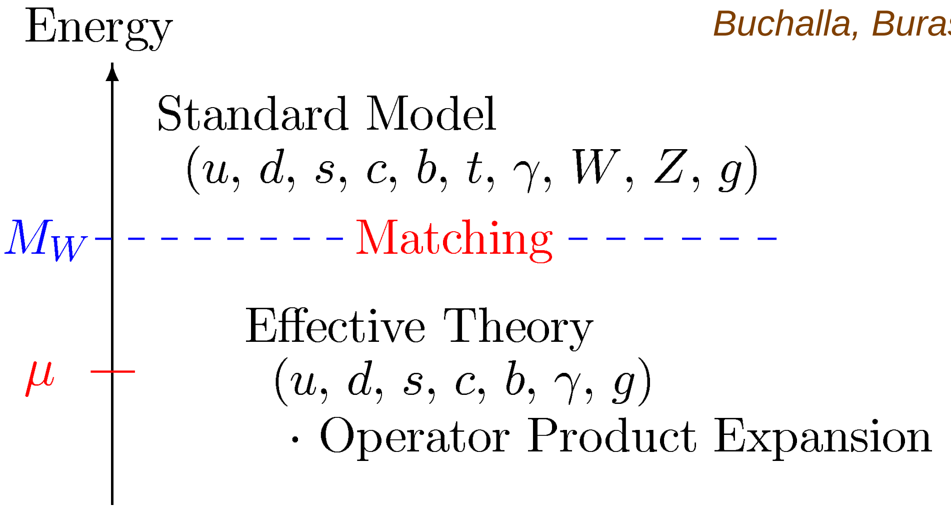
$\beta = \phi_1$

- In the SM,
  $S_{J/\psi K_S} = S_{\phi K_S} + \mathcal{O}(\lambda^2)$.
- Belle : $S_{\phi K_S}$ indicates a 3.5σ deviation from the SM prediction.
- There is a 2.1σ discrepancy between BABAR and Belle.

$\Longrightarrow$ We consider New Physics contributions in $B \to \phi K$.

Effective Hamiltonian for B Decays

Buchalla, Buras, Lautenbacher, Rev.Mod.Phys.68,1125,1996



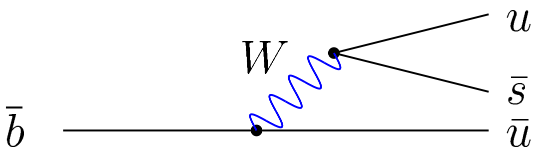
$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\rm CKM} C_i(\mu) O_i(\mu)$$

μ : Factorization scale

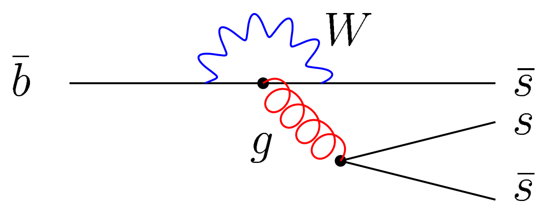
New Physics $\Longrightarrow C_{3-6},\ C_{7\gamma},\ C_{8g}$

Standard Model

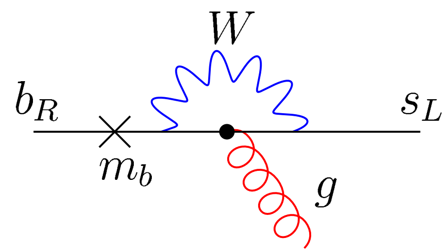
Tree



Penguin



Magnetic Penguin



Effective Theory

$$O_1^{(q)} = (\bar{s}_i q_j)_{V-A} (\bar{q}_j b_i)_{V-A}\ , \qquad O_2^{(q)} = (\bar{s}_i q_i)_{V-A} (\bar{q}_j b_j)_{V-A}\ ,$$

$$O_{3,5} = (\bar{s}_i b_i)_{V-A} \sum_q (\bar{q}_j q_j)_{V\mp A}\ , \quad O_{4,6} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V\mp A}\ ,$$

$$O_{7\gamma} = \frac{e}{8\pi^2} m_b (\bar{s} \sigma^{\mu\nu} (1+\gamma_5) b) F_{\mu\nu}\ , \quad O_{8g} = -\frac{g_s}{8\pi^2} m_b (\bar{s}_i \sigma^{\mu\nu} (1+\gamma_5) T^a_{ij} b_j) G^a_{\mu\nu}$$

Strong Phases and CP Asymmetries

$$a_{\phi K_S}(t) = A_{\phi K_S}\cos(\Delta M t) + S_{\phi K_S}\sin(\Delta M t)$$

If there is any new physics in $B \to \phi K_S$,

$$\begin{aligned} A(\phi K_S) &= |A^{\rm SM}|e^{i\delta_{SM}} + |A^{\rm NP}|e^{i\theta_{NP}}e^{i\delta_{NP}} \\ \overline{A}(\phi K_S) &= |\overline{A}^{\rm SM}|e^{i\delta_{SM}} + |\overline{A}^{\rm NP}|e^{-i\theta_{NP}}e^{i\delta_{NP}} \end{aligned}$$

$\delta_{SM(NP)}$: Strong phase, θ_{NP} : CP violating phase

(Final-state interaction phase)

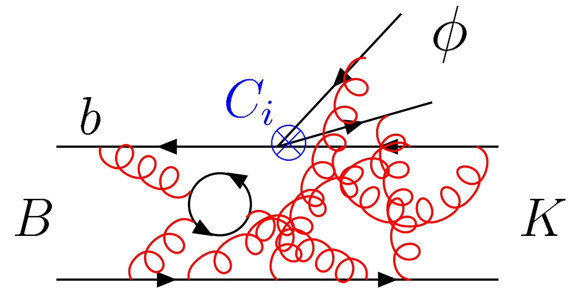
$$S_{\phi K_S} = \frac{\sin 2\phi_1 + 2\left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|\cos\delta\sin(\theta_{NP}+2\phi_1) + \left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|^2\sin(2\theta_{NP}+2\phi_1)}{1+2\left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|\cos\delta\cos\theta_{NP} + \left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|^2}$$

$$A_{\phi K_S} = \frac{2\left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|\sin\delta\sin\theta_{NP}}{1+2\left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|\cos\theta_{\rm NP}\cos\delta + \left|\frac{A^{\rm NP}}{A^{\rm SM}}\right|^2} \qquad \delta \equiv \delta_{SM} - \delta_{NP}$$

$\Longrightarrow$ δ and $\left|A^{\rm NP}/A^{\rm SM}\right|$ are needed.

How to Calculate Matrix Elements

$\langle \phi K | O_i(\mu) | B \rangle = ?$



Generalized factorization, QCD factorization,
Perturbative QCD, Light-cone QCD sum rules,
Lattice QCD, Soft-collinear effective theory, etc.

- Generalized Factorization Approach
- QCD Factorization (QCDF or BBNS)

(See e.g. Beneke, Buchalla, Neubert, Sachrajda, NPB606,245,2001)

$\Longrightarrow$ These approaches were used for estimating new physics contributions in $B \to \phi K_S$ decay.

(Khalil, Kou, PRD67,055009,2003, Kane et al. PRL94,141803,2003, $\cdots$)

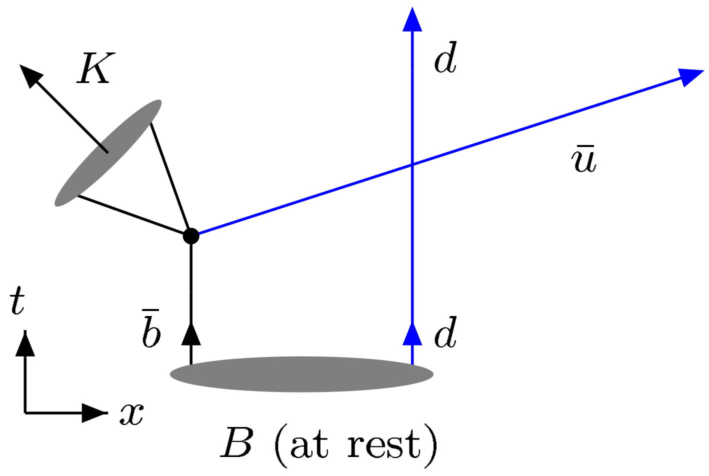
In this study, we use another approach :

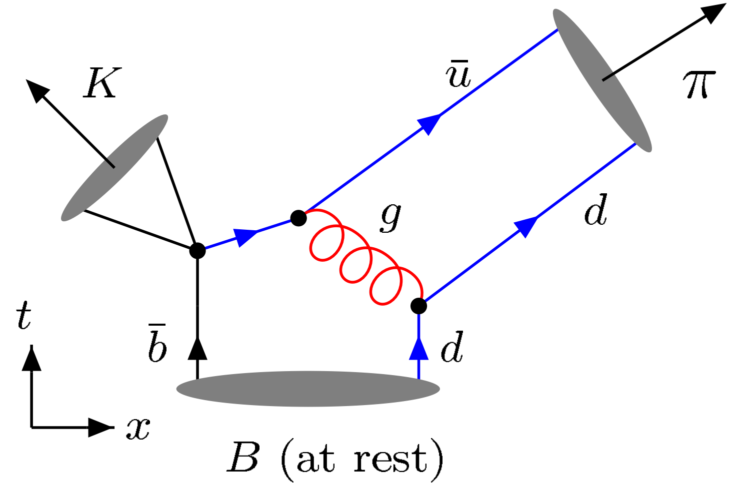
- Perturbative QCD (PQCD) *(See e.g. Keum, Li, Sanda, PRD63,054008,2001)*

A dominant source of strong phase in PQCD is different from in QCDF.
Although it is difficult to discover NP by PQCD, it can be applied as a guide for NP search.

2. PQCD Approach in B Meson Decays

An Intuitive Picture of the PQCD Approach





The spectator quark (d quark) exchanges a hard gluon and it lines itself with the fast $\bar{u}$ quark so that it forms π^- meson.

- We consider the form factor is dominated by hard gluon exchanges.
- Are contributions from many soft gluon exchanges actually small ?

  $\Longrightarrow$ We calculate other contributions, which are calculable perturbatively, and compare the predictions with data.

Review of PQCD

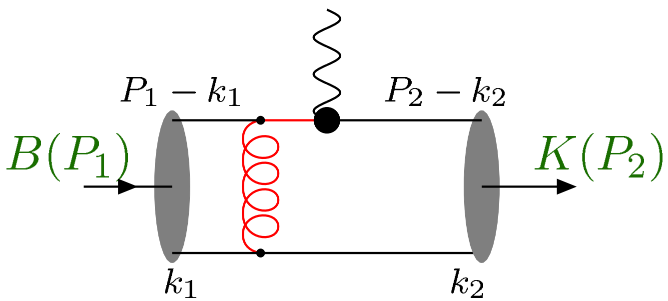
- Factorization Theorem : *(Brodsky, Lepage, PRD22,2157,1980)*

$$\langle M_2(P_2)M_3(P_3)|H_{\rm eff}|B(P_1)\rangle$$

$$= \int [dx_i]\Phi_{M_2}(x_2,P_2)\Phi_{M_3}(x_3,P_3)C(t)H(x_1,x_2,x_3,t)\Phi_B(x_1,P_1)$$

$t \sim O(M_B)$, x_i are the momentum fractions of partons.

- End-Point Singularity in H



$$\propto \frac{1}{(k_1-k_2)^2}\cdot\frac{1}{(P_1-k_2)^2}$$

$$= \frac{1}{-x_1x_2M_B^2 - |\mathbf{k_{1T}} - \mathbf{k_{2T}}|^2}\cdot\frac{1}{-x_2M_B^2 - |\mathbf{k_{2T}}|^2}$$

$$\simeq \frac{1}{x_1x_2^2M_B^2}$$

$$\Phi_K(x_2) \propto x_2(1-x_2)$$

Light-Cone Coordinate

$$P = (P^+, P^-, \mathbf{P}_T)$$

$$P^\pm = \frac{1}{\sqrt{2}}(P^0 \pm P^3)$$

$$\mathbf{P}_T = (P^1, P^2)$$

$$P_1 = \frac{M_B}{\sqrt{2}}(1,1,\mathbf{0}_T) \qquad P_2 = \frac{M_B}{\sqrt{2}}(0,1,\mathbf{0}_T)$$

$$k_1 = (x_1P_1^+, 0, \mathbf{k}_{1T}) \qquad k_2 = (0, x_2P_2^-, \mathbf{k}_{2T})$$

$$0 \le x_{1,2} \le 1$$

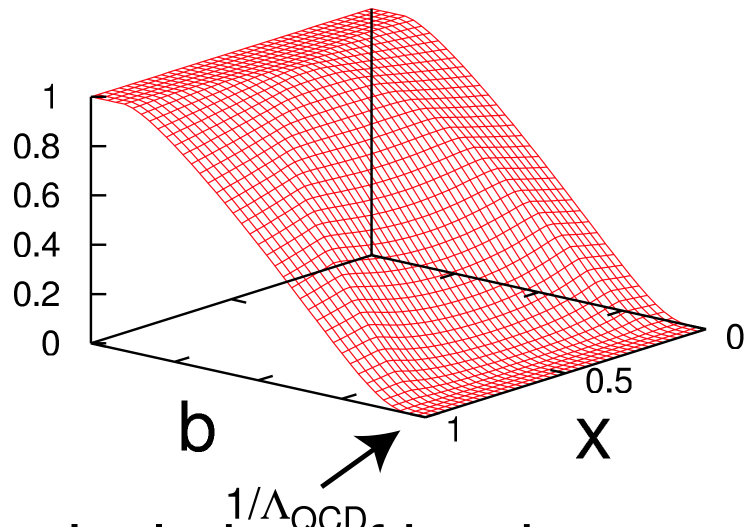
Sudakov Factor in QCD *Botts, Sterman, NPB325,62,1989*

When we retain k_T, the large double logarithms are generated from the overlap of collinear and soft divergence in radiative corrections to meson wave functions.

$\Longrightarrow$ Sudakov factor

$\Longrightarrow$ Large b (small k_T) is suppressed.

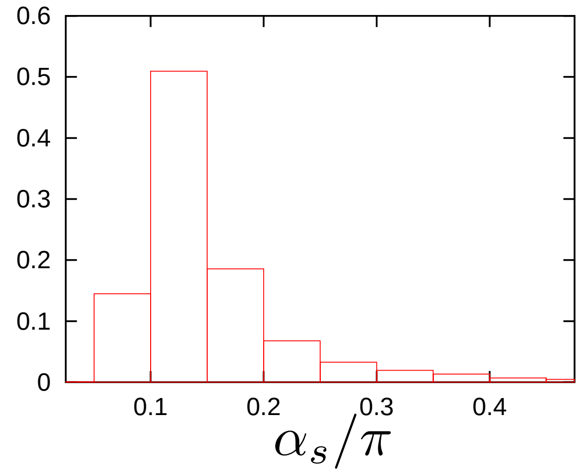
$$\Psi(P, \mathbf{k}_T) = \int d^2\mathbf{b}\, e^{i\,\mathbf{k}_T\cdot\mathbf{b}}\, \Psi(P, \mathbf{b})$$



- Sudakov factor ensures a perturbative calculation of hard part.

$$\frac{1}{q^2} = \frac{1}{-x_1 x_2 M_B^2 - |\mathbf{k_{1T}} - \mathbf{k_{2T}}|^2}$$

No End-Point Singularity !!

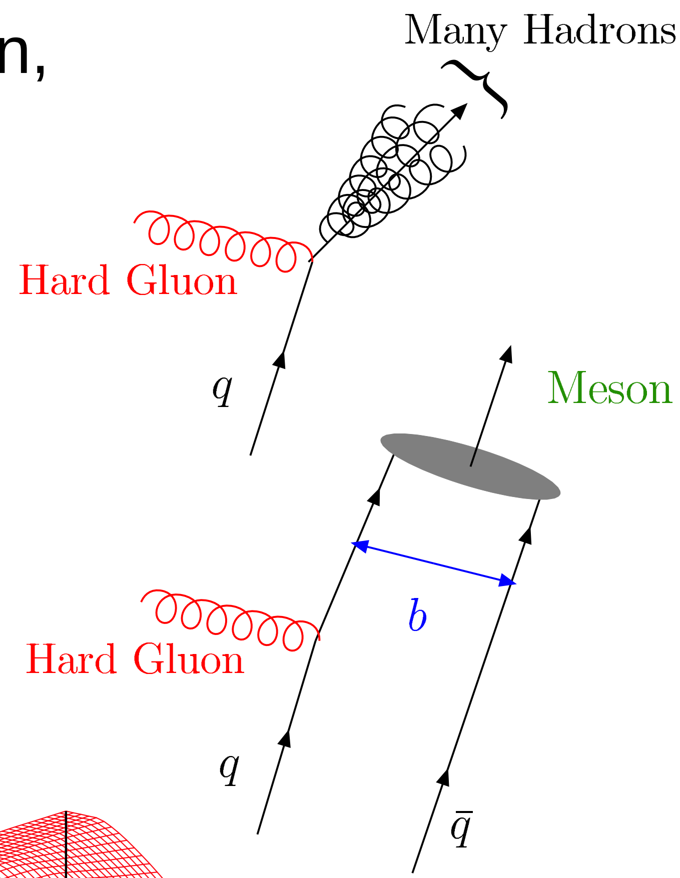


$\Longrightarrow$ We have checked self-consistency in our calculations.

Physical Meaning of Sudakov Factor in b space

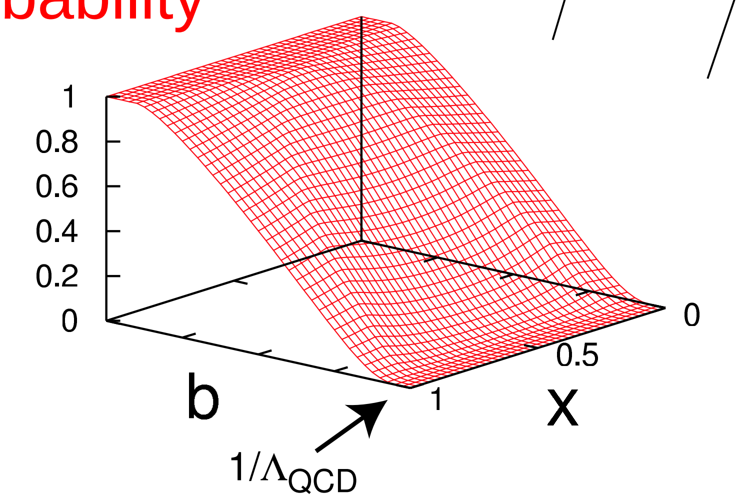
- If a single quark interacts with a hard gluon, it must emit many collinear gluons.

  $\Longrightarrow$ Not exclusive processes !!



- If a $q\bar{q}$ pair with small separation b interacts with a hard gluon, it emits no gluons since it is a color singlet.

- The Sudakov factor gives a probability for no emitted gluons.



Review of PQCD

- k_T Factorization Theorem : *(Li, Sterman, NPB381,129,1992)*

$$\text{Amp.} = \int [dx_i][db_{iT}]\Phi_K(x_2, b_{2T})\Phi_\phi(x_3, b_{3T})C(t)\, H(x_i, b_{iT}, t)\Phi_B(x_1, b_{1T})e^{-S}$$

- Non-perturbative part $\Longrightarrow$ Meson wave functions :
  - K, ϕ $\Longleftarrow$ Light-cone QCD sum rules

    (Ball,JHEP01,010,1999; Ball,Braun,Koike,Tanaka,NPB529,323,1998)
  - B $\Longleftarrow$ Model function

$$\Phi_B \sim (\not{P} + M_B)\gamma_5 x^2(1-x)^2 \exp\left[-\frac{1}{2}\left(\frac{xM_B}{\omega_B}\right)^2 - \frac{\omega_B^2 b^2}{2}\right], \quad \omega_B = 0.36 \sim 0.44\ \text{GeV}$$

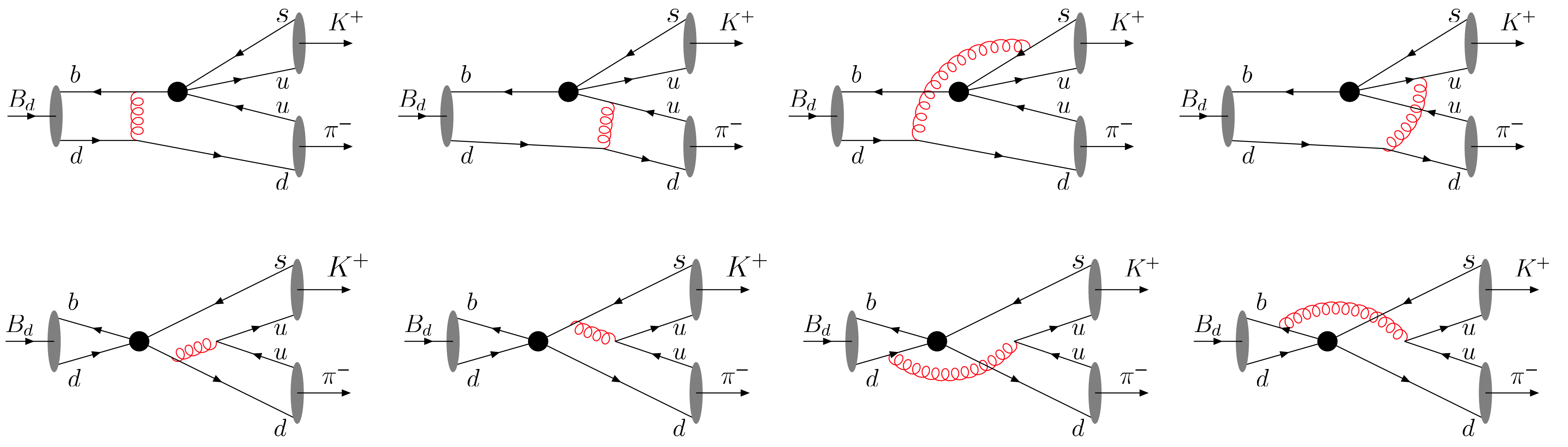
- Theoretical Errors
  - Large theoretical uncertainty comes from Φ_B.

    $\Longrightarrow$ These errors are reduced in **CP** asymmetries.
  - We expect that higher-order corrections are about 30%.

    $\Longrightarrow$ We suppose these corrections are reduced in **CP** asymmetries.

Review of PQCD

The leading order diagrams in PQCD:



Review of PQCD

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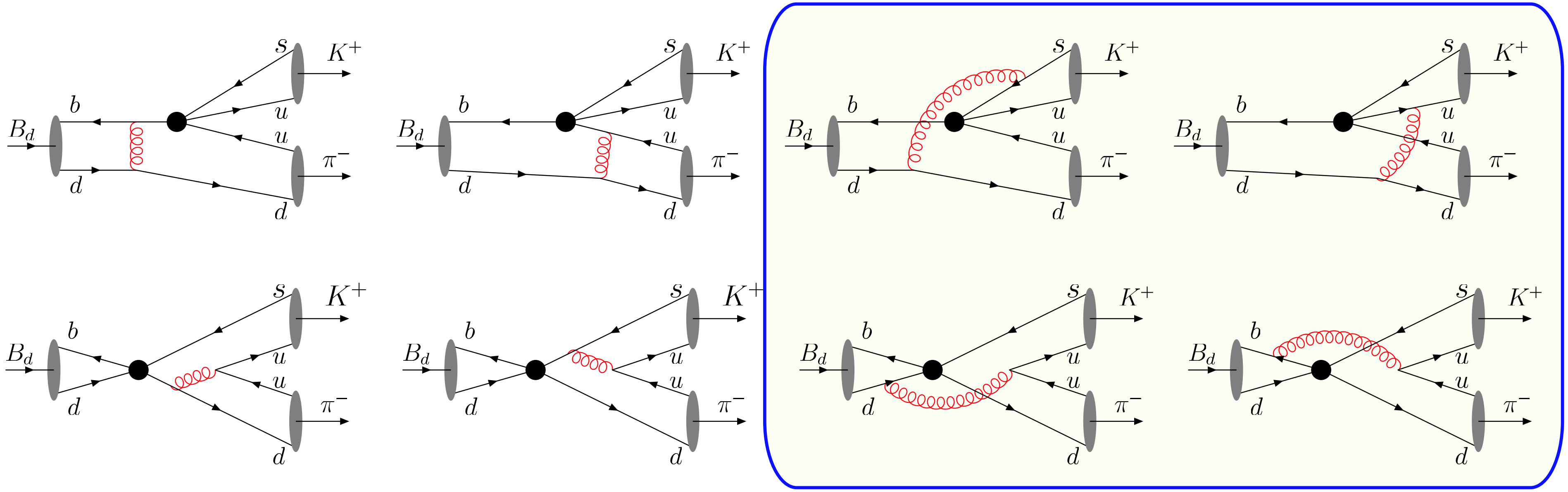

- Non-factorizable diagrams are calculable.

Review of PQCD

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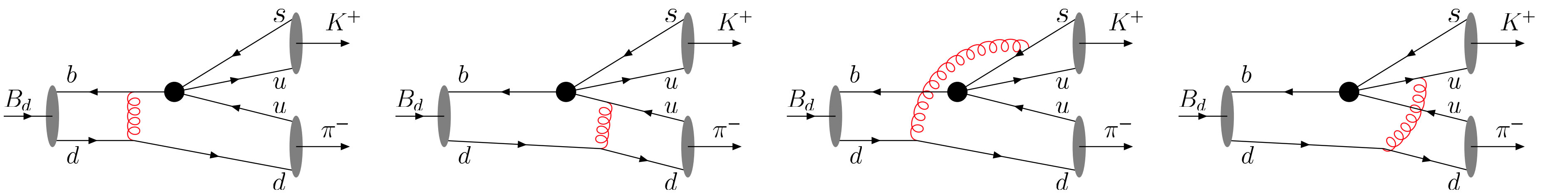

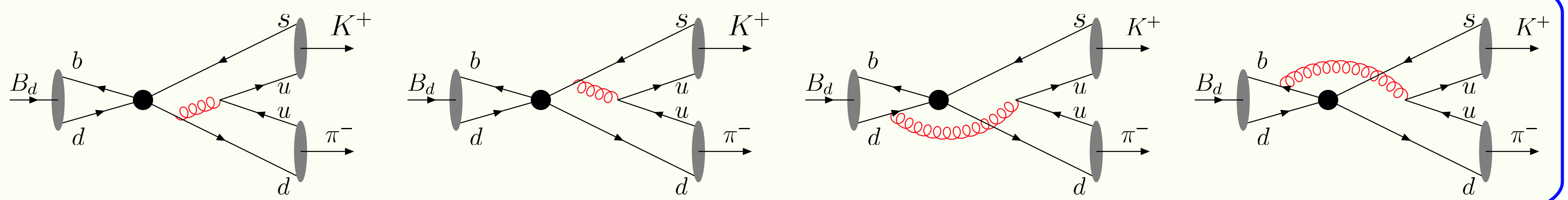

- Non-factorizable diagrams are calculable.
- Annihilation diagrams are also calculable.

Review of PQCD

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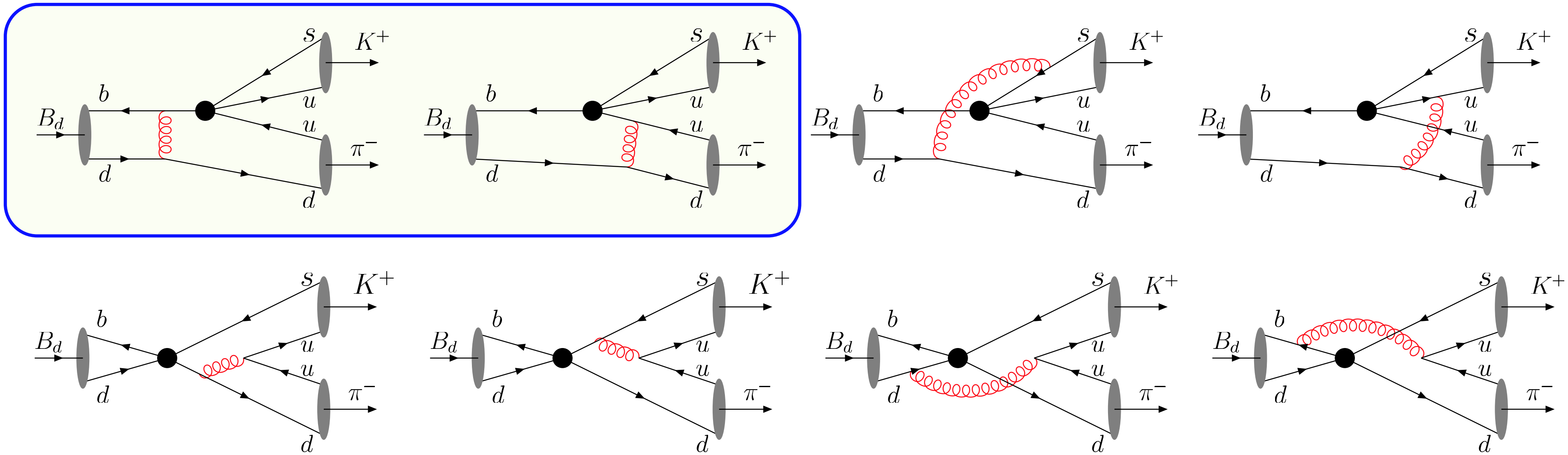

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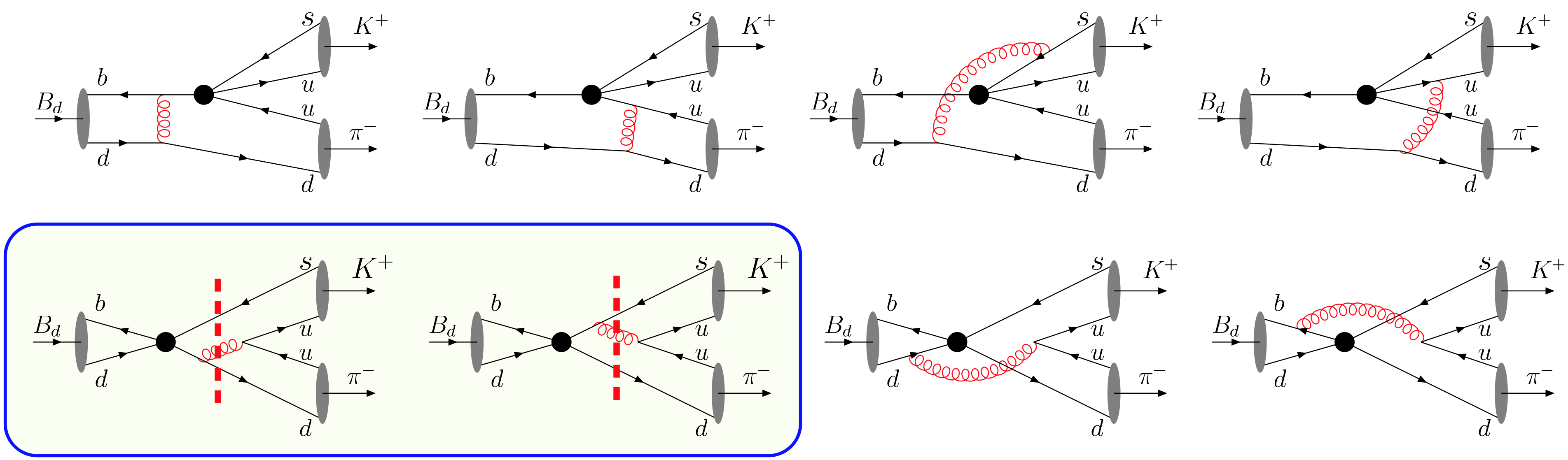
- Annihilation diagrams are also calculable.
- Factorizable diagrams are dominant.

Review of PQCD

The leading order diagrams in PQCD:



- Non-factorizable diagrams are calculable.
- Annihilation diagrams are also calculable.
- Factorizable diagrams are dominant.
- Factorizable annihilation diagrams generate a large strong phase.

$$\frac{1}{(1-x_2)x_3 M_B^2 - |\boldsymbol{k}_{2T} - \boldsymbol{k}_{3T}|^2} = (\text{Pri. val.}) - i\,\pi\,\delta\left((1-x_2)x_3 M_B^2 - |\boldsymbol{k}_{2T} - \boldsymbol{k}_{3T}|^2\right)$$

Applications of the PQCD approach

PQCD has been applied to various charmless B decays:

$K\pi$	*Keum, Li, Sanda, Phys.Lett.B504,6,2001:Phys.Rev.D63,054008,2001*
$\pi\pi$	*Lu, Ukai, Yang, Phys.Rev.D63,074009,2001*
KK	*Chen, Li, Phys.Rev.D63,014003,2001*
$K\eta^{(\prime)}$	*Kou, Sanda, Phys.Lett.B525,240,2002*
$\rho\pi$, $\omega\pi$	*Lu, Yang, Eur.Phys.J.C23,275,2002*
ρK, ωK	*Chen, Phys.Lett.B525,56,2002*
ϕK	*Mishima, Phys.Lett.B521, 252,2001: Chen, Keum, Li, Phys.Rev.D64,112002,2001*
$\phi\pi$	*Melic, Phys.Rev.D59,074005,1999*
$K^*\pi$	*Keum, hep-ph/0210127*
ϕK^*	*Chen, Keum, Li, Phys.Rev.D66,054013,2002*
$K^*\gamma$	*M. Matsumori will talk on this workshop.*

Branching ratios (10^{-6}) and Direct CP Asymmetries

Y. Y. Keum and A. I. Sanda, eConf ***C0304052****, WG420 (2003).*

	BABAR	Belle	PQCD
$B \to \pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$4.4 \pm 0.6 \pm 0.3$	$5.93 - 10.99$
$B^\pm \to \pi^\pm\pi^0$	$5.5\ ^{+1.0}_{-0.9} \pm 0.6$	$5.0 \pm 1.2 \pm 0.5$	$2.72 - 4.79$
$B \to \pi^0\pi^0$	$2.1 \pm 0.6 \pm 0.3$	$1.7 \pm 0.6 \pm 0.2$	$0.33 - 0.65$
$B \to K^\pm\pi^\mp$	$17.9 \pm 0.9 \pm 0.7$	$18.5 \pm 1.0 \pm 0.7$	$12.67 - 19.30$
$B^\pm \to K^\pm\pi^0$	$12.8\ ^{+1.2}_{-1.1} \pm 1.0$	$12.0 \pm 1.3\ ^{+1.3}_{-0.9}$	$7.87 - 14.21$
$B^\pm \to K^0\pi^\pm$	$22.3 \pm 1.7 \pm 1.1$	$22.0 \pm 1.9 \pm 1.1$	$14.43 - 26.26$
$B \to K^0\pi^0$	$11.4 \pm 1.7 \pm 0.8$	$11.7 \pm 2.3\ ^{+1.2}_{-1.3}$	$7.92 - 14.27$
$A_{\rm CP}(\pi^\pm\pi^\mp)$	$0.19 \pm 0.19 \pm 0.05$	$0.77 \pm 0.27 \pm 0.08$	$0.160 \sim 0.300$
$A_{\rm CP}(\pi^\pm\pi^0)$	$-0.03\ ^{+0.18}_{-0.17} \pm 0.02$	$-0.14 \pm 0.24^{+0.05}_{-0.04}$	0.0
$A_{\rm CP}(K^\pm\pi^\mp)$	$-0.107 \pm 0.041 \pm 0.013$	$-0.088 \pm 0.035 \pm 0.018$	$-0.219 \sim -0.129$
$A_{\rm CP}(K^\pm\pi^0)$	$-0.09 \pm 0.09 \pm 0.01$	$0.23 \pm 0.11\ ^{+0.01}_{-0.04}$	$-0.173 \sim -0.100$
$A_{\rm CP}(K^0\pi^\pm)$	$-0.05 \pm 0.08 \pm 0.01$	$0.07\ ^{+0.09}_{-0.08}\ ^{+0.01}_{-0.03}$	$-0.015 \sim -0.006$

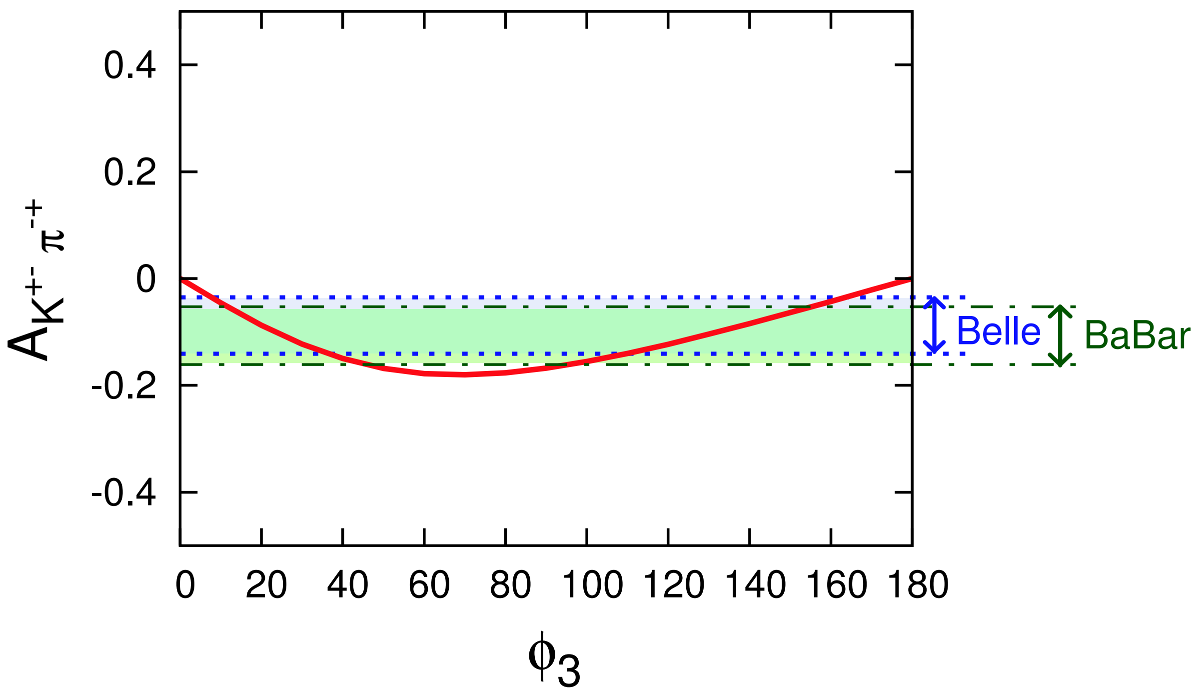
PQCD Prediction for $A_{K^{\mp}\pi^{\pm}}$

Direct CP asymmetry for $B \to K^{\mp}\pi^{\pm}$

Exp. :

BABAR	Belle	CLEO	Average
$-0.107 \pm 0.041 \pm 0.013$	$-0.088 \pm 0.035 \pm 0.018$	$-0.04 \pm 0.16 \pm 0.02$	-0.095 ± 0.028

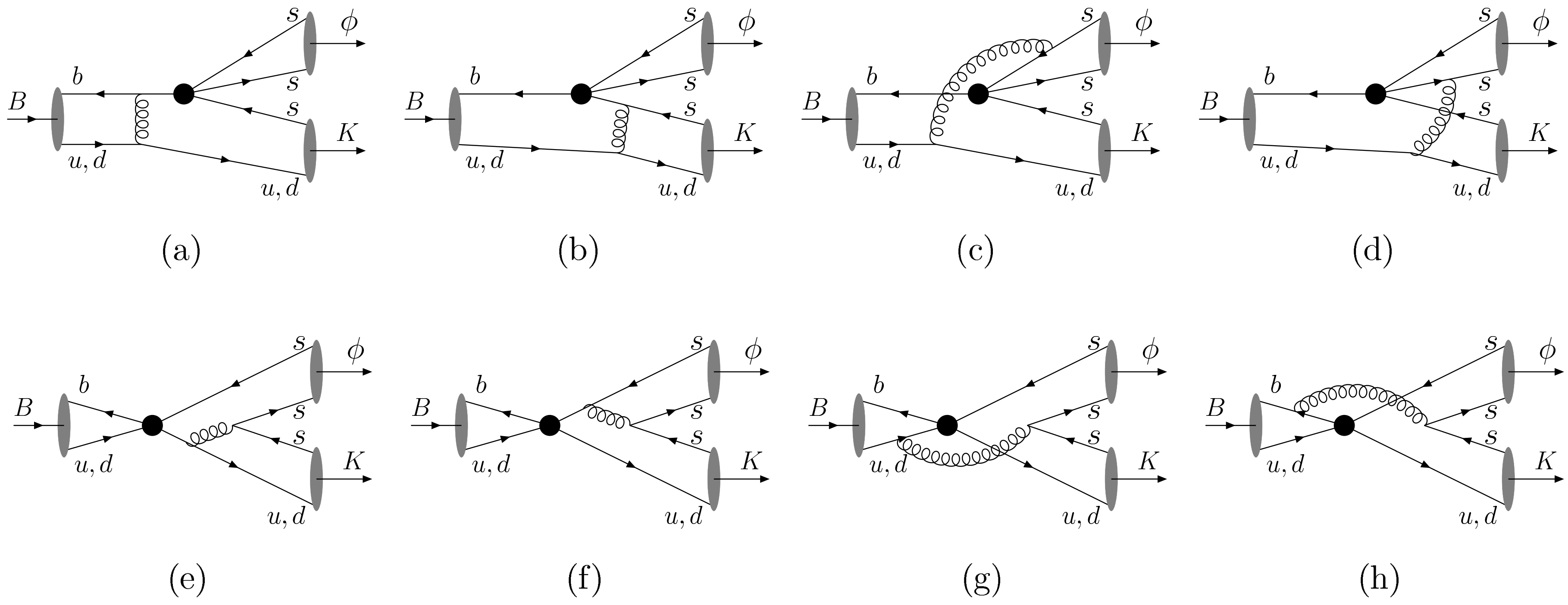
PQCD :



PQCD prediction is negative and in agreement with exp. data.

$B \to \phi K$ Decays in the PQCD Approach

Mishima, Phys.Lett.B521,252,2001
Chen, Keum, Li, PRD64,112002,2001



- (a) and (b) are dominant.
- Branching ratios are larger than those in factorization approaches.

Mode	Exp.(BABAR)	Exp.(Belle)	Result
$B^0 \to \phi K^0$	$(8.4^{+1.5}_{-1.3} \pm 0.5) \times 10^{-6}$	$(9.0^{+2.2}_{-1.8} \pm 0.7) \times 10^{-6}$	$(8.5^{+3.0}_{-2.0}) \times 10^{-6}$
$B^\pm \to \phi K^\pm$	$(10.0^{+0.9}_{-0.8} \pm 0.5) \times 10^{-6}$	$(9.4 \pm 1.1 \pm 0.7) \times 10^{-6}$	$(9.3^{+3.1}_{-2.1}) \times 10^{-6}$

$\Longrightarrow$ PQCD predictions are in agreement with exp. data.

3. MSSM Contribution in B Decays

SUSY Contributions in B Decays

We consider supersymmetric contribution (MSSM) in B decays.

- There are new sources of CP Violation and Flavor Changing Neutral Current.
  - Gluino contributions
  - Chargino contributions
  - Neutralino contributions

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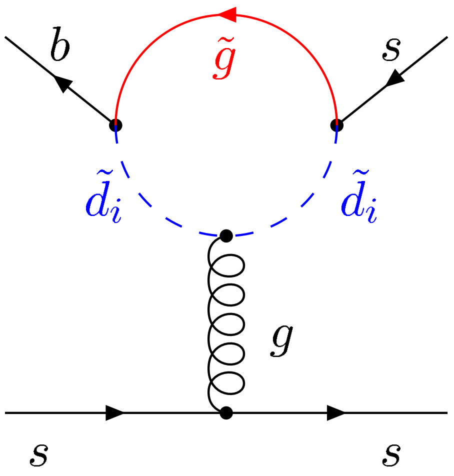

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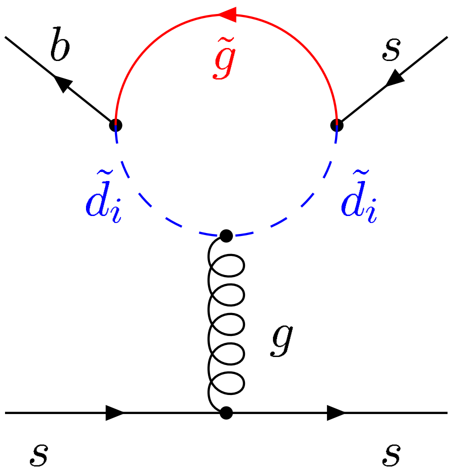
  - ~~Chargino contributions~~
  - ~~Neutralino contributions~~



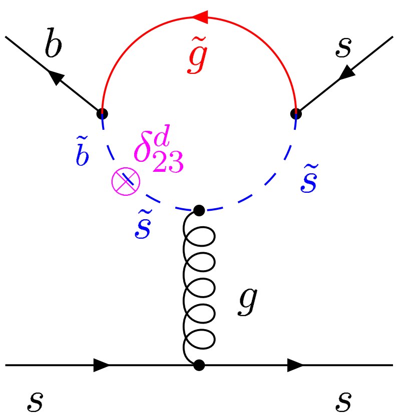
- We use Mass Insertion Approximation. *(Hall, Kostelecky, Raby, NPB267,415,1986)*

  Off-diagonal elements in the squark mass matrix produce FCNC.

Squark mass matrix :

$$M_{\tilde{d}}^2 = \begin{pmatrix} m_{\tilde{d},LL}^2 & m_{\tilde{d},LR}^2 \\ m_{\tilde{d},RL}^2 & m_{\tilde{d},RR}^2 \end{pmatrix} \Longrightarrow \delta_{LL,ij}^d \equiv \frac{(V_d^\dagger m_{\tilde{d},LL}^2 V_d)_{ij}}{m_{\tilde{q}}^2} \ll 1$$

$(i \neq j) \qquad LL \to LR, RL, RR$

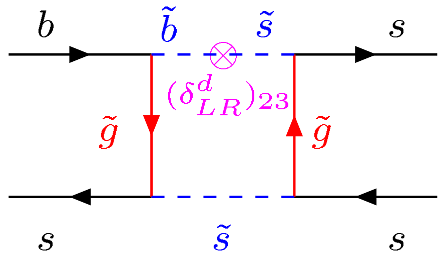


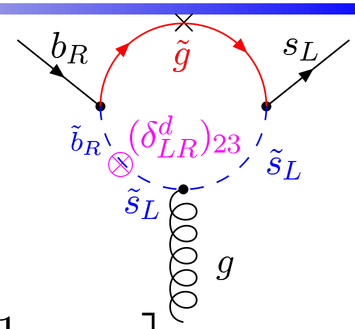
Wilson Coefficients in MSSM

Gabbiani, Gabrielli, Masiero, Silvestrini, NPB477,321,1996

Gluino contributions

in Penguin and Magnetic Penguin :





$$C_3(M_S) \simeq -\frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[-\frac{1}{9}B_1(x) - \frac{5}{9}B_2(x) - \frac{1}{18}P_1(x) - \frac{1}{2}P_2(x)\right]$$

$$C_4(M_S) \simeq -\frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[-\frac{7}{3}B_1(x) + \frac{1}{3}B_2(x) + \frac{1}{6}P_1(x) + \frac{3}{2}P_2(x)\right]$$

$$C_5(M_S) \simeq -\frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[\frac{10}{9}B_1(x) + \frac{1}{18}B_2(x) - \frac{1}{18}P_1(x) - \frac{1}{2}P_2(x)\right]$$

$$C_6(M_S) \simeq -\frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[-\frac{2}{3}B_1(x) + \frac{7}{6}B_2(x) + \frac{1}{6}P_1(x) + \frac{3}{2}P_2(x)\right]$$

$$C_{7\gamma}(M_S) \simeq \frac{\sqrt{2}\alpha_s\pi}{6G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}\left[(\delta^d_{LL})_{23}\frac{8}{3}M_3(x) + (\delta^d_{LR})_{23}\frac{m_{\tilde{g}}}{m_b}\frac{8}{3}M_1(x)\right]$$

$$C_{8g}(M_S) \simeq \frac{\sqrt{2}\alpha_s\pi}{2G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}\left[(\delta^d_{LL})_{23}\left(\frac{1}{3}M_3(x) + 3M_4(x)\right) + (\delta^d_{LR})_{23}\frac{m_{\tilde{g}}}{m_b}\left(\frac{1}{3}M_1(x) + 3M_2(x)\right)\right]$$

$$x \equiv m_{\tilde{g}}^2 / m_{\tilde{q}}^2$$

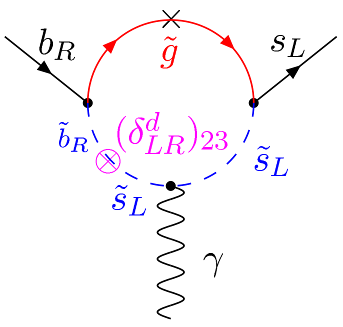
New Operators: $C_i O_i \xrightarrow{L \leftrightarrow R} \widetilde{C}_i \widetilde{O}_i$

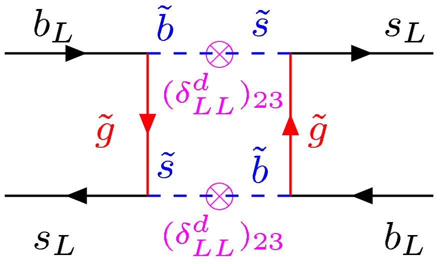
We consider single mass insertions:

- LR insertion : $(\delta^d_{LR})_{23}$
- RL insertion : $(\delta^d_{RL})_{23}$
- LL insertion : $(\delta^d_{LL})_{23}$
- RR insertion : $(\delta^d_{RR})_{23}$

and constrain them from $b \to s$ FCNC processes:

- $\mathrm{Br}(B \to X_s\gamma)$
- $A_{\mathrm{CP}}(B \to X_s\gamma)$
- $B_s - \overline{B}_s$ Mixing: ΔM_s

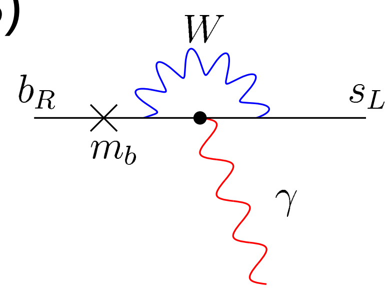




$\Longrightarrow$ The constraint from $\mathrm{Br}(B \to X_s\gamma)$ is strong.

Constraint from $B \to X_s\gamma$ *Kagan, Neubert, Eur.Phys.J.C7,5,1999*

$$\mathrm{Br}(B \to X_s\gamma) = (3.3 \pm 0.4) \times 10^{-4} \quad \text{(PDG2003)}$$



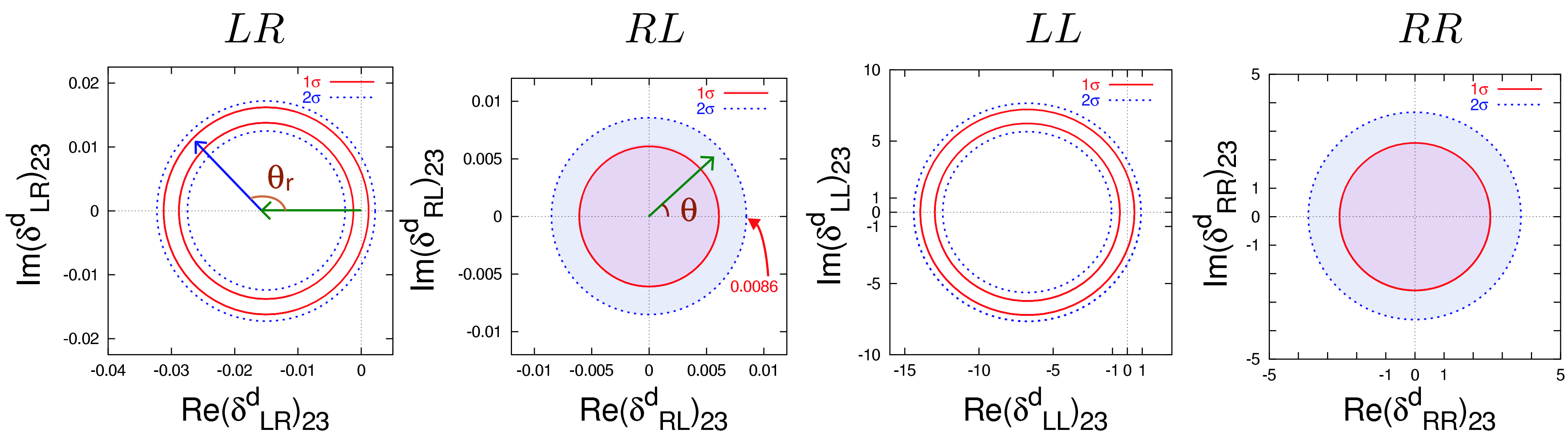
$$\mathrm{Br}(B \to X_s\gamma) \propto |C_{7\gamma}(m_b)|^2 + |\tilde{C}_{7\gamma}(m_b)|^2$$

$$C_{7\gamma}(m_b) = C_{7\gamma}^{\mathrm{SM}}(m_b) + C_{7\gamma}^{\mathrm{NP}}(m_b)$$
$$\tilde{C}_{7\gamma}(m_b) = \tilde{C}_{7\gamma}^{\mathrm{NP}}(m_b)$$

$$C_{7\gamma}^{\mathrm{NP}}(M_S) \simeq \frac{\sqrt{2}\alpha_s\pi}{6G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}\left[(\delta_{LL}^d)_{23}\frac{8}{3}M_3(x) + (\delta_{LR}^d)_{23}\frac{m_{\tilde{g}}}{m_b}\frac{8}{3}M_1(x)\right]$$

$m_{\tilde{g}} = m_{\tilde{q}} = 500$ GeV

We take $(\delta^d)_{23}$ in 2σ region.



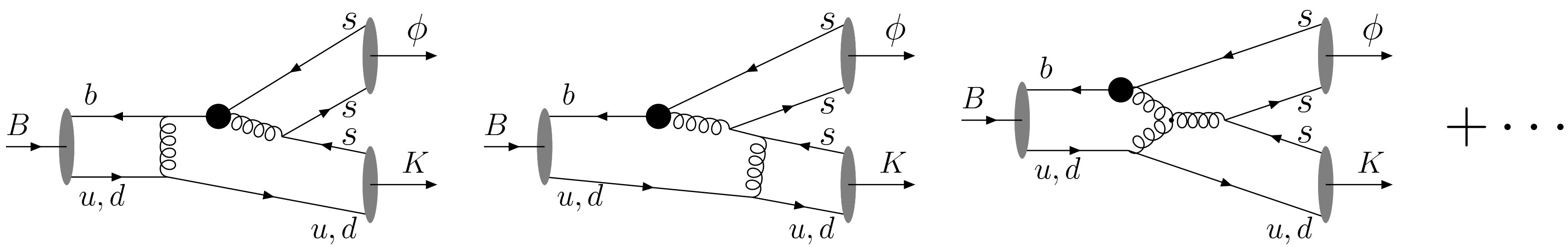
4. MSSM Effects on $B \to \phi K$ Decays

Magnetic Penguin in PQCD

Mishima, Sanda, Prog.Theor.Phys.110(2003)549 [hep-ph/0305073]

Magnetic Penguin is important to a search for New Physics.

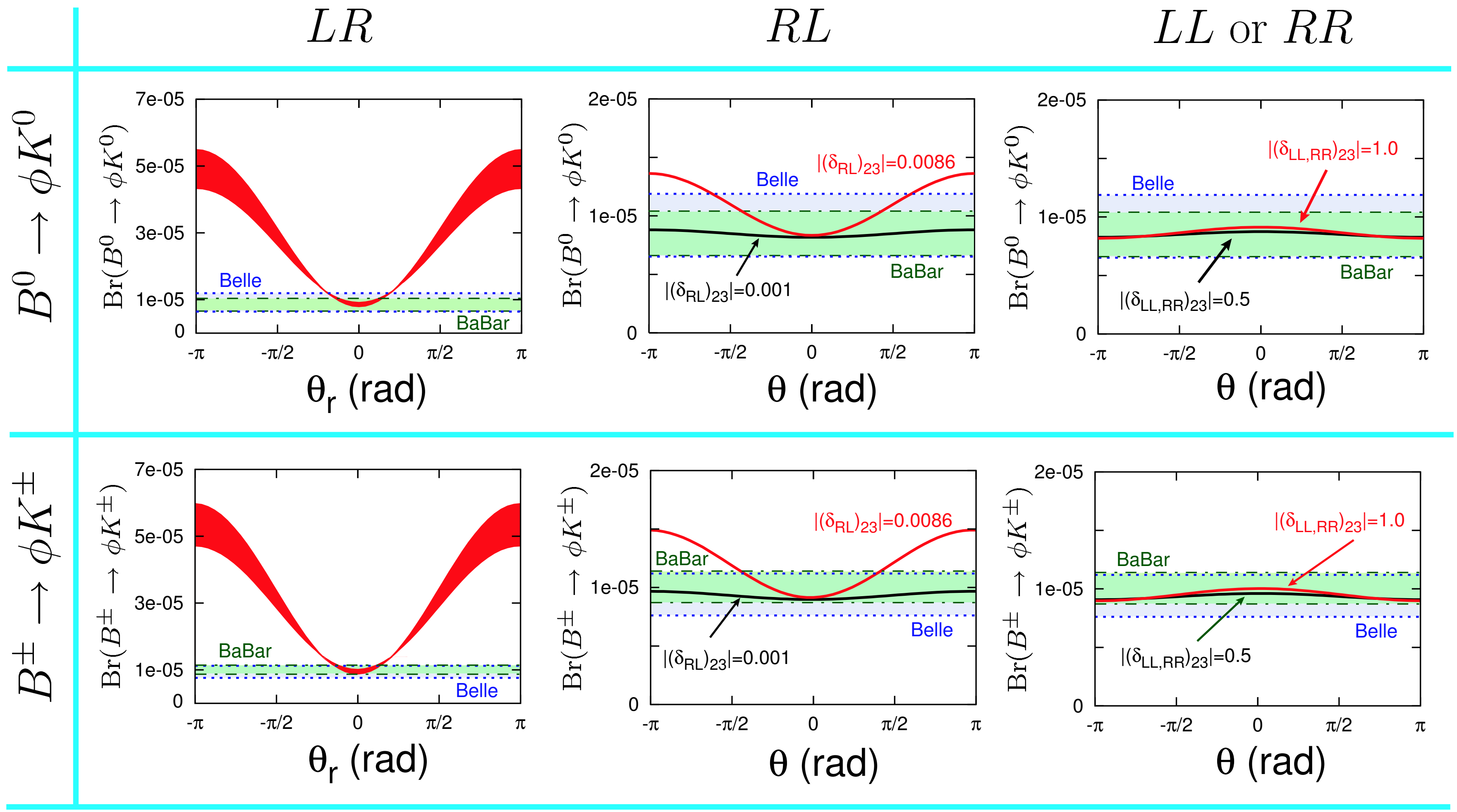
$$O_{8g} = -\frac{g_s}{8\pi^2} m_b (\bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) T^a_{ij} b_j) G^a_{\mu\nu}$$



- Above diagrams are dominant.
- Strong phase comes from their absorptive part.
- A relative strong phase between Penguin and MP is large.

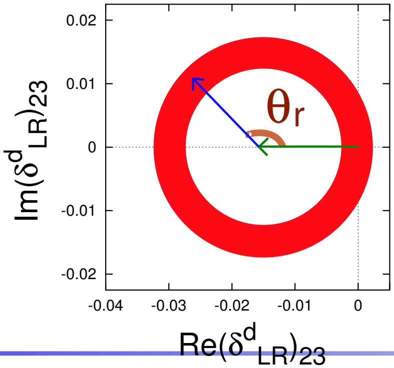
$\Longrightarrow$ If there is a new CP-violating phase in MP, then $A_{\phi K}$ might change significantly from the SM prediction.

Branching Ratios



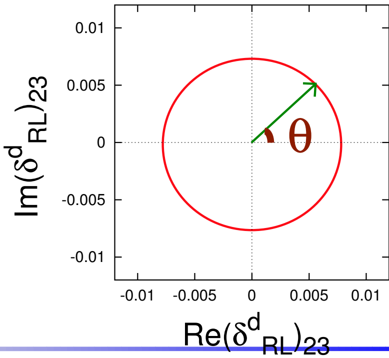
LR :

$(\delta^d_{LR})_{23} = -0.015 + r\, e^{i\theta_r}$

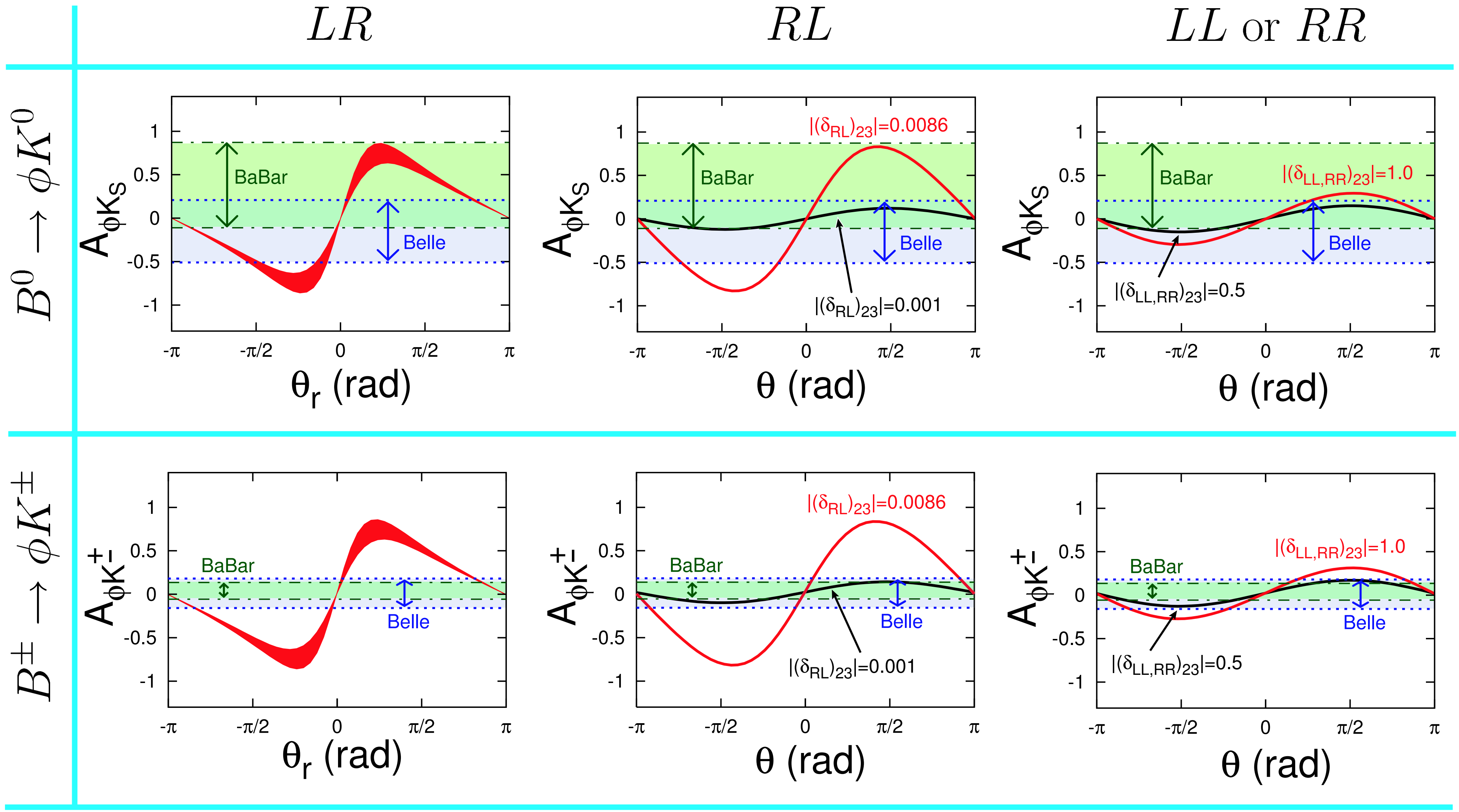


RL, LL, RR :

$(\delta^d)_{23} = |(\delta^d)_{23}|\, e^{i\theta}$



Direct CP Asymmetries $A_{\phi K}$

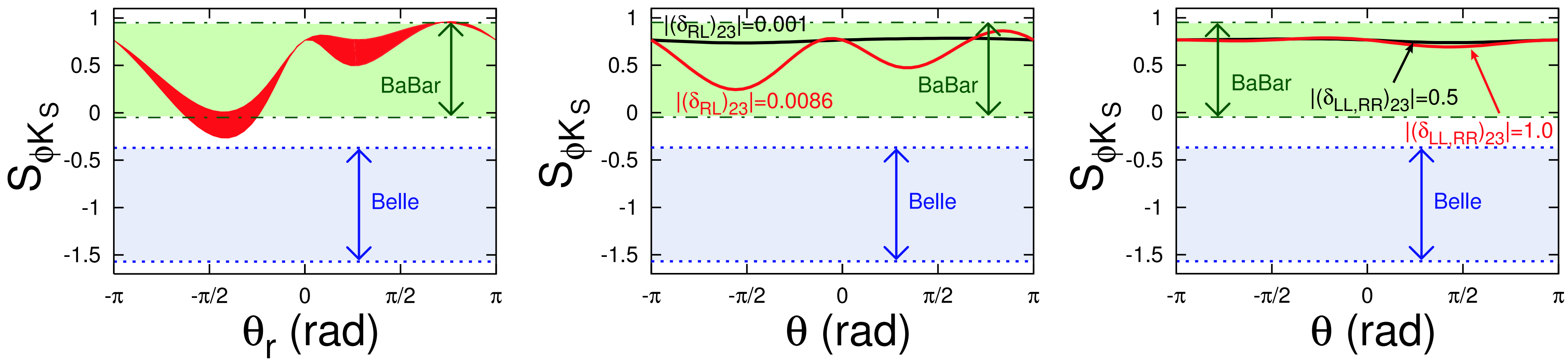


- $-0.85 \lesssim A_{\phi K} \lesssim 0.85$
- $A_{\phi K_S} \simeq A_{\phi K^\pm}$

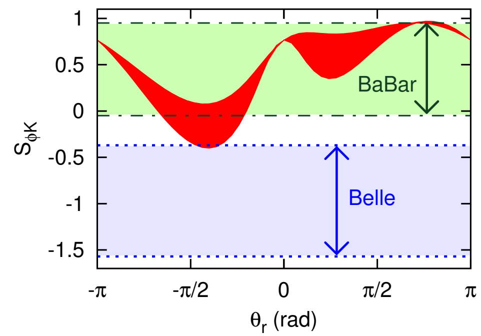
$A_{\phi K}$ are generated from the interference between penguin and magnetic-penguin.

Indirect CP Asymmetries $S_{\phi K}$

LR $\quad$ RL $\quad$ LL or RR



- $S_{\phi K_S} \gtrsim -0.28$
- It is difficult to explain the current Belle data.
- We attempted to maximize MSSM effects, $S_{\phi K_S}$ had been larger than about -0.4.



$m_{\tilde{g}} = 200$GeV

$m_{\tilde{q}} = 2$ TeV

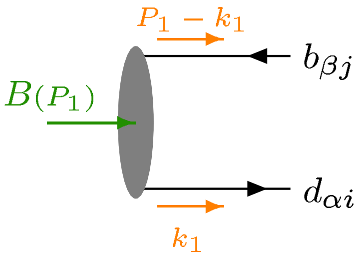
5. Summary

- We calculated MSSM contributions with a mass insertion in $B \to \phi K$ decays using the PQCD approach.
  - $-0.85 \lesssim A_{\phi K} \lesssim 0.85$
  - $A_{\phi K_S} \simeq A_{\phi K^\pm}$
  - $S_{\phi K_S} \gtrsim -0.28$
- It is difficult to explain the current Belle data.
- Experimental Error (only statistical)
  - 2003 : 140 fb^{-1} $\delta S_{\phi K_S} \sim 0.50$
  - $\sim$ 2005 : 300 fb^{-1} $\delta S_{\phi K_S} \sim 0.34$
  - 2008 $\sim$: 1 ab^{-1} $\delta S_{\phi K_S} < 0.1$
- We need more theoretical study in $B \to \phi K$ decays.

Backup

Meson Wave Functions

B meson wave function:



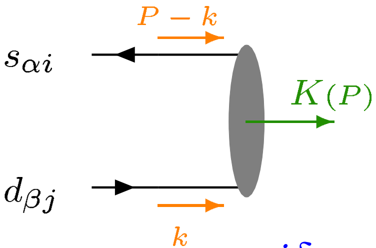
$$\equiv \langle 0|\bar{b}_{\beta j}(0) d_{\alpha i}(z)|B(P_1)\rangle$$

$i,\ j$: color indices

$\alpha,\ \beta$: spinor indices

$$= \frac{\delta_{ij}}{\sqrt{2N_c}} \int dx_1 d^2\mathbf{k}_{1T} e^{-i(x_1 P_1^- z^+ - \mathbf{k}_{1T}\mathbf{z}_T)} \left[(\not{P}_1 + M_B)\gamma_5 \phi_B(x_1, \mathbf{k}_{1T})\right]_{\alpha\beta}$$

K meson wave function:



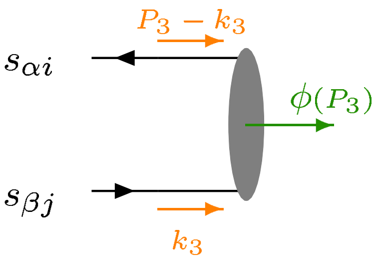
$$\equiv \langle K(P_2)|\bar{d}_{\beta j}(0) s_{\alpha i}(z)|0\rangle$$

$$m_{0K} = \frac{M_K^2}{m_d + m_s} = 1.7\ \mathrm{GeV},$$

$$n_\mu \equiv z_\mu / z^-,\ v_\mu \equiv P_{2\mu}/P_2^+$$

$$= \frac{-i\delta_{ij}}{\sqrt{2N_c}} \int_0^1 dx_2 e^{ix_2 P_2 \cdot z} \gamma_5 \left[\not{P}_2 \phi_K^A(x_2) + m_{0K}\phi_K^P(x_2) + m_{0K}(\not{v}\ \not{n} - 1)\phi_K^T(x_2)\right]_{\alpha\beta}$$

ϕ meson wave function:



$$\equiv \langle \phi(P_3)|\bar{s}_{\beta j}(0) s_{\alpha i}(z)|0\rangle$$

$$= \frac{\delta_{ij}}{\sqrt{2N_c}} \int_0^1 dx_3 e^{ix_3 P_3 \cdot z} \left[M_\phi\ \not{\epsilon}_\phi \phi_\phi(x_3) + \not{\epsilon}_\phi\ \not{P}_3 \phi_\phi^t(x_3) + M_\phi \phi_\phi^s(x_3)\right]_{\alpha\beta}$$

Meson Distribution Amplitudes

$$\phi_B(x,b) = N_B x^2(1-x)^2 \exp\left[-\frac{1}{2}\left(\frac{xM_B}{\omega_B}\right)^2 - \frac{\omega_B^2 b^2}{2}\right] , \quad \omega_B = 0.36 \sim 0.44 \text{ GeV}$$

$$\phi_K^A(x) = \frac{f_K}{2\sqrt{2N_c}} 6x(1-x)\left[1 + a_1 C_1^{\frac{3}{2}}(1-2x) + a_2 C_2^{\frac{3}{2}}(1-2x)\right] , \quad \rho_K = (m_d+m_s)/M_K$$

$$\phi_K^P(x) = \frac{f_K}{2\sqrt{2N_c}}\left[1 + \left(30\eta_3 - \frac{5}{2}\rho_K^2\right) C_2^{\frac{1}{2}}(1-2x) - 3\left\{\eta_3\omega_3 + \frac{9}{20}\rho_K^2(1+6a_2)\right\} C_4^{\frac{1}{2}}(1-2x)\right]$$

$$\phi_K^T(x) = \frac{f_K}{2\sqrt{2N_c}}(1-2x)\left[1 + 6\left(5\eta_3 - \frac{1}{2}\eta_3\omega_3 - \frac{7}{20}\rho_K^2 - \frac{3}{5}\rho_K^2 a_2\right)(1-10x+10x^2)\right]$$

$C_n^\nu(x)$: Gegenbauer polynomial

$$a_1 = -0.18 , \quad a_2 = 0.16 , \quad \eta_3 = 0.015 , \quad \omega_3 = -3.0 \quad \Longleftarrow$$

Light-cone QCD sum rules

Ball, JHEP.01:010,1999

$$\phi_\phi(x) = \frac{f_\phi}{2\sqrt{2N_c}} 6x(1-x)$$

$$+ \frac{3}{2}\delta_+\left\{1 - (1-2x)\log\frac{1-x}{x}\right\}\right]$$

$$\phi_\phi^t(x) = \frac{f_\phi^T}{2\sqrt{2N_c}}\left[3(1-2x)^2 + \frac{35}{4}\zeta_3^T\{3 - 30(1-2x)^2 + 35(1-2x)^4\} \quad \nwarrow\right.$$

$$\phi_\phi^s(x) = \frac{f_\phi^T}{4\sqrt{2N_c}}\left[(1-2x)\left\{6 + 9\delta_+ + 140\zeta_3^T(1-10x+10x^2)\right\} + 3\delta_+\log\frac{x}{1-x}\right]$$

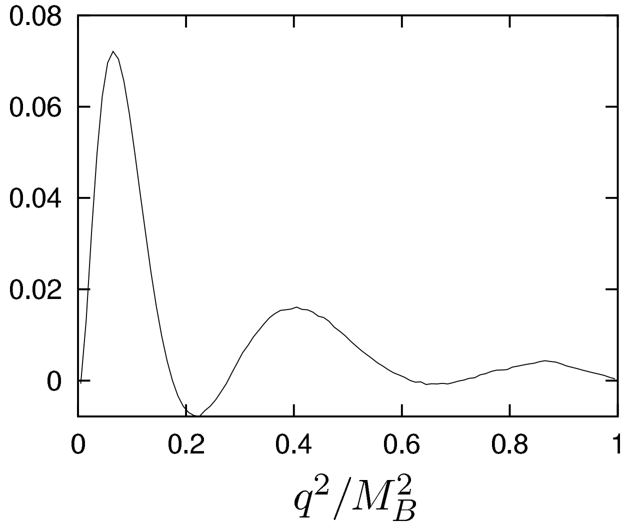
$$\zeta_3^T = 0.024 , \quad \delta_+ = 0.46 \quad \Longleftarrow$$

Light-cone QCD sum rules

Ball, Braun, Koike, Tanaka, Nucl.Phys.B529:323,1998

q^2-dependence of Magnetic Penguin Amplitudes

The distribution of q^2 for $\mathrm{Re}\mathcal{M}_a^{MP}$:



$$\Longrightarrow \quad \langle q^2 \rangle = 6.3\ \text{GeV}^2 \sim M_B^2/4$$

The shape of this graph is not simple.