Connecting B_d and B_s decays through QCD factorisation and flavour symmetries

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Two-body nonleptonic B decays

Bunch of B_d and B_s, same underlying CKM mechanism in SM

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and see whether these correlations are upset by New Physics

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Idea : Exploit both to extract SM correlations
Illustration : $B_{d,s} \to K^0 \bar{K}^0$ and $B_{d,s} \to K^{*0} \bar{K}^{*0}$

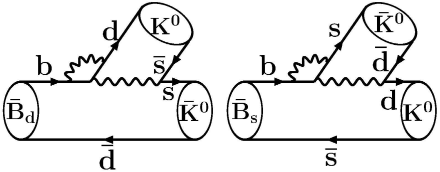
SDG, J. Matias and J. Virto, PRL97:061801,2006 and arXiv:0705.0477

Penguin-mediated decays

$B_q \to K^0\bar{K}^0$: interesting penguin decays

Conventional tree and penguin decomposition

$$\begin{aligned}\bar{A} \equiv A(\bar{B}_q \to K^0\bar{K}^0) &= V_{ub}V_{uq}^* T_K^q + V_{cb}V_{cq}^* P_K^q \\ A \equiv A(B_q \to K^0\bar{K}^0) &= V_{ub}^* V_{uq} T_K^q + V_{cb}^* V_{cq} P_K^q\end{aligned}$$



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no contribution from O_1 and O_2

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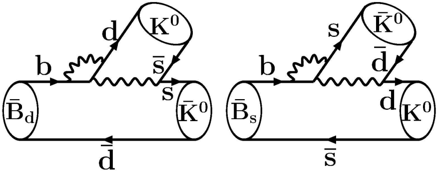

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Difference between tree and penguin from the u, c quark in loop

$\Longrightarrow \Delta = T - P$ dominated by short-distance physics computed fairly accurately within QCDF

$$\begin{aligned}\Delta_K^d &= (1.09 \pm 0.43) \cdot 10^{-7} + i(-3.02 \pm 0.97) \cdot 10^{-7}\,\mathrm{GeV} \\ \Delta_K^s &= (1.03 \pm 0.41) \cdot 10^{-7} + i(-2.85 \pm 0.93) \cdot 10^{-7}\,\mathrm{GeV}\end{aligned}$$

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- Longitudinal observables : Br, A_{dir}, A_{mix}
- Longitudinal amplitude described by

$$\begin{aligned}\bar{A}_0 \equiv A(\bar{B}_q \to K^{*0}\bar{K}^{*0})^{\mathrm{long}} &= V_{ub}V_{uq}^{*}T_{K^*}^{q} + V_{cb}V_{cq}^{*}P_{K^*}^{q} \\ A_0 \equiv A(B_q \to K^{0}\bar{K}^{0})^{\mathrm{long}} &= V_{ub}^{*}V_{uq}T_{K^*}^{q} + V_{cb}^{*}V_{cq}P_{K^*}^{q}\end{aligned}$$

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$\Delta = T - P$ also accurate in QCDF for $B_{d,s} \to K^{*0}\bar{K}^{*0}$

$$\begin{aligned} \Delta^d_{K^*} &= (1.48 \pm 0.57) \cdot 10^{-7} + i(-1.15 \pm 0.85) \cdot 10^{-7}\mathrm{GeV} \\ \Delta^s_{K^*} &= (1.29 \pm 0.50) \cdot 10^{-7} + i(-1.00 \pm 0.74) \cdot 10^{-7}\mathrm{GeV} \end{aligned}$$

CKM angles from penguin-mediated decays

Relations between $T - P$, decay observables and CKM matrix elements

- B_d and B_s decays differ through mixing angles
- $b \to d$ and $b \to s$ differ through CKM elements for tree and penguin

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- B_d decay through $b \to d$, e.g. $B_d \to K^{(*)0} \bar{K}^{(*)0}$
- B_d decay through $b \to s$, e.g. $B_d \to \phi K_S$

$$\sin^2 \alpha = \frac{\widetilde{BR}}{2|\lambda_u^{(D)}|^2 |\Delta|^2} \left(1 - \sqrt{1 - (\mathcal{A}_{\rm dir})^2 - (\mathcal{A}_{\rm mix})^2}\right)$$

$$\sin^2 \beta = \frac{\widetilde{BR}}{2|\lambda_c^{(D)}|^2 |\Delta|^2} \left(1 - \sqrt{1 - (\mathcal{A}_{\rm dir})^2 - (\mathcal{A}_{\rm mix})^2}\right)$$

with $\widetilde{BR} = BR\times$ trivial kinematic factor

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$$\begin{aligned}
\sin^2 \beta_s &= \frac{\widetilde{BR}}{2|\lambda_c^{(D)}|^2|\Delta|^2} \left(1 - \sqrt{1 - (\mathcal{A}_{\rm dir})^2 - (\mathcal{A}_{\rm mix})^2}\right) \\
\sin^2 (\beta_s + \gamma) &= \frac{\widetilde{BR}}{2|\lambda_u^{(D)}|^2|\Delta|^2} \left(1 - \sqrt{1 - (\mathcal{A}_{\rm dir})^2 - (\mathcal{A}_{\rm mix})^2}\right)
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For penguin-mediated decays,

- $T - P$ accurately known from QCDF (assumed in following)
  $T - P$, BR, $\mathcal{A}_{\rm dir}$, $\mathcal{A}_{\rm mix}$ and UT sides $\Longrightarrow$angles
- If $T - P$ affected by charming penguins
  Probe their size by determining $T - P$ from the above relations

$$B_{d,s} \to K^0 \bar{K}^0$$

$T-P$: Hadronic parameters for $B_d \to K^0\bar{K}^0$

To extract the hadronic parameters of this decay

- Unknowns $|T|$, $|P/T|$ and $arg(P/T)$
- Observables $Br = (0.96 \pm 0.26) \cdot 10^{-6}$, A_{dir} (broad range), A_{mix}

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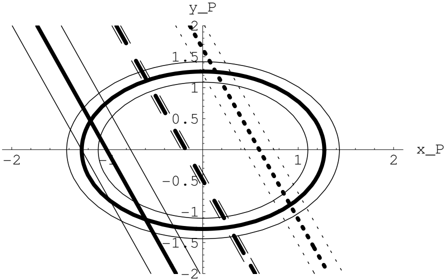


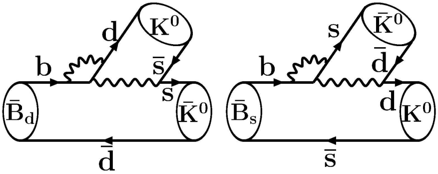
$$P = (x_P + iy_P) \cdot 10^{-6} \text{ GeV}$$

- $Br + (T-P) \Longrightarrow$ a circle
- $A_{dir} + (T-P) \Longrightarrow$ a strip

From left to right
$A_{dir} = -0.17, -0.03, 0.10$
(QCDF : $A_{dir} \simeq 0.20$)

Intersection : hadronic parameters up to a two-fold ambiguity

$B_d \to K^0 \bar{K}^0$ and $B_s \to K^0 \bar{K}^0$: U-spin



Final state $K^0 \bar{K}^0$ invariant
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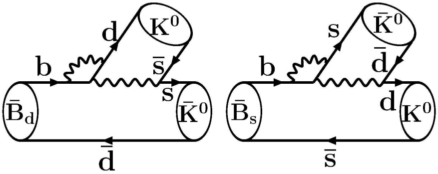

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U-spin breaking only in a few places :

- Difference in form factors $f = M^2_{B_s} F_0^{\bar{B}_s \to K}(0)/[M^2_{B_d} F_0^{\bar{B}_d \to K}(0)]$

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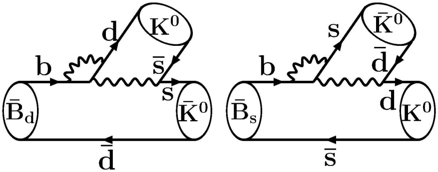

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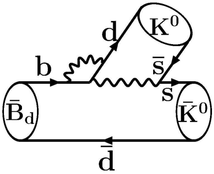

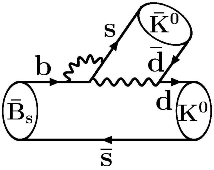

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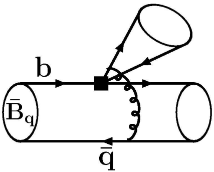
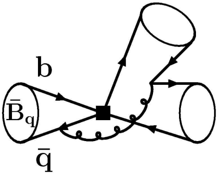


Hard-spectator scattering
(B_d and B_s distribution amplitudes)



Weak annihilation
(gluon emission off light quark)

$B_d \to K^0\bar{K}^0$ and $B_s \to K^0\bar{K}^0$: QCDF

In QCD factorisation

$$\frac{P^{s0}}{fP^{d0}} = 1 + \frac{A^d_{KK}}{P^{d0}}\left\{\delta\alpha_4^c - \frac{\delta\alpha^c_{4EW}}{2} + \delta\beta_3^c + 2\delta\beta_4^c - \frac{\delta\beta^c_{3EW}}{2} - \delta\beta^c_{4EW}\right\}$$

$$\frac{T^{s0}}{fT^{d0}} = 1 + \frac{A^d_{KK}}{T^{d0}}\left\{\delta\alpha_4^u - \frac{\delta\alpha^u_{4EW}}{2} + \delta\beta_3^u + 2\delta\beta_4^u - \frac{\delta\beta^u_{3EW}}{2} - \delta\beta^u_{4EW}\right\}$$

with normalisation $A^q_{KK} = M^2_{B_q} F_0^{\bar{B}_q\to K}(0) f_K G_F/\sqrt{2}$

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U-spin breaking in very few places

- factorisable ratio $f = M^2_{B_s} F_0^{\bar{B}_s \to K}(0)/[M^2_{B_d} F_0^{\bar{B}_d \to K}(0)]$
- $\delta\alpha_i = \alpha_i^p\big|_{B_s} - \alpha_i^p\big|_{B_d}$: hard-spectator scattering
- $\delta\beta_i = \beta_i^p\big|_{B_s} - \beta_i^p\big|_{B_d}$: weak annihilation

$\Longrightarrow$Very small differences in agreement with U-spin arguments

QCDF bounds : $\left|\frac{P^{s0}}{fP^{d0}} - 1\right| \leq 5\%$ and $\left|\frac{T^{s0}}{fT^{d0}} - 1\right| \leq 5\%$

Observables in $B_s \to K^0\bar{K}^0$ and K^+K^-

$B_d \to K^0\bar{K}^0$: Br, A_{dir}, $T^{d0} - P^{d0}$
$\Longrightarrow B_d \to K^0\bar{K}^0$: T^{d0} and P^{d0} (ratios)

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A_{dir}^{d0}	$BR^{s0} \times 10^6$	$A_{dir}^{s0} \times 10^2$	$A_{mix}^{s0} \times 10^2$
-0.2	$18.4 \pm 6.5 \pm 3.6$	0.8 ± 0.3	-0.3 ± 0.8
-0.1	$18.2 \pm 6.4 \pm 3.6$	0.4 ± 0.3	-0.7 ± 0.7
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Also QCDF/U-spin connection for $B_d \to K^0\bar{K}^0$ and $B_s \to K^+K^-$ pengs.
(but not for tree : QCDF estimate for $B_s \to K^+K^-$)

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$$
\begin{aligned}
Br(B_s \to K^+K^-) &= (20 \pm 8 \pm 4 \pm 2) \cdot 10^{-6} \\
Br(B_s \to K^0\bar{K}^0) &= (18 \pm 6 \pm 4 \pm 2) \cdot 10^{-6}
\end{aligned}
$$

CDF measurement [Beauty 2006]: $BR^{s\pm} = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$

$$B_d \longrightarrow K^{*0}\bar{K}^{*0} \text{ vs } B_s \longrightarrow K^{*0}\bar{K}^{*0}$$

ϕ_s from $\mathcal{A}_{\rm mix}$ by bounding T/P

$$\mathcal{A}_{\rm mix}^{\rm long}(B_s \to K^{*0}\bar{K}^{*0}) \simeq \sin\phi_s + 2\left|\frac{\lambda_u^{(s)}}{\lambda_c^{(s)}}\right| \mathrm{Re}\left(\frac{T^s_{K^*K^*}}{P^s_{K^*K^*}}\right)\sin\gamma\cos\phi_s + \cdots$$

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- both pieces $O(\lambda^2)$
- $|\lambda_u^{(s)}/\lambda_c^{(s)}| = 0.044$ small but ${\rm Re}(T/P)$?

$$ {\rm Re}\left(\frac{T}{P}\right) = {\rm Re}\left(\frac{P+\Delta}{P}\right) = 1 + {\rm Re}\left(\frac{\Delta}{P}\right)$$

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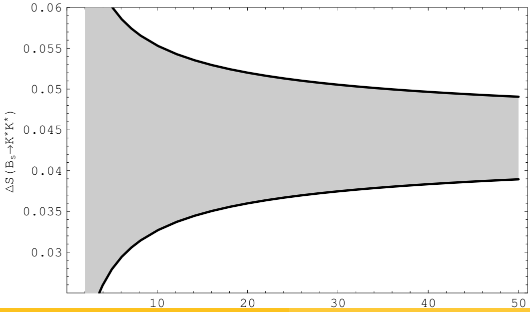


Bounds on
$$\Delta S(B_s \to K^{*0}\bar{K}^{*0}) = 2\left|\frac{\lambda_u^{(s)}}{\lambda_c^{(s)}}\right| \mathrm{Re}\left(\frac{T^s_{K^*K^*}}{P^s_{K^*K^*}}\right)\sin\gamma\cos\phi_s$$
as a function of
$$BR^{\rm long}(B_s \to K^{*0}\bar{K}^{*0}) \cdot 10^6$$

Relating B_d and B_s in SM

$$P^s_{K^*K^*} = f\, P^d_{K^*}(1+\delta^P_{K^*}) \quad T^s_{K^*K^*} = f\, T^d_{K^*}(1+\delta^T_{K^*}) \quad f = \frac{m^2_{B_s} A_0^{B_s\to K^*}}{m^2_B A_0^{B\to K^*}}$$

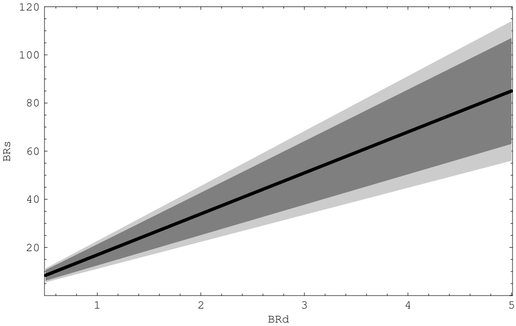
U-spin expectations and QCDF computations : $|\delta^P_{K^*}| \le 0.12 \quad |\delta^T_{K^*}| \le 0.15$

Relating B_d and B_s in SM

$$P^s_{K^*K^*} = f\, P^d_{K^*}(1+\delta^P_{K^*}) \quad T^s_{K^*K^*} = f\, T^d_{K^*}(1+\delta^T_{K^*}) \quad f = \frac{m^2_{B_s} A_0^{B_s\to K^*}}{m^2_B A_0^{B\to K^*}}$$

U-spin expectations and QCDF computations : $|\delta^P_{K^*}| \leq 0.12 \quad |\delta^T_{K^*}| \leq 0.15$

$B_d \to K^{*0}\bar{K}^{*0}$: Br, A_{dir}, $T^d_{K^*} - P^d_{K^*}$
$\Longrightarrow B_d \to K^{*0}\bar{K}^{*0}$: $T^s_{K^{*0}}$ and $P^s_{K^{*0}}$ $\Longrightarrow$observables



$BR^{\rm long}(B_s \to K^{*0}\bar{K}^{*0}) \cdot 10^6$
in terms of
$BR^{\rm long}(B_d \to K^{*0}\bar{K}^{*0}) \cdot 10^6$

(light : f,
dark : other hadr inputs)

Relating B_d and B_s in SM and beyond

Assuming $\phi_s^{SM} = 2\beta_s = -2^\circ$, $56^\circ \leq \gamma \leq 68^\circ$,
and $BR^{\rm long}(B_d \to K^{*0}\bar{K}^{*0}) \gtrsim 5 \times 10^{-7}$

$$\left(BR^{\rm long}(B_s \to K^{*0}\bar{K}^{*0})/BR^{\rm long}(B_d \to K^{*0}\bar{K}^{*0})\right)_{SM} = 17 \pm 6$$

$$\mathcal{A}_{\rm dir}^{\rm long}(B_s \to K^{*0}\bar{K}^{*0})_{SM} = 0.000 \pm 0.014$$

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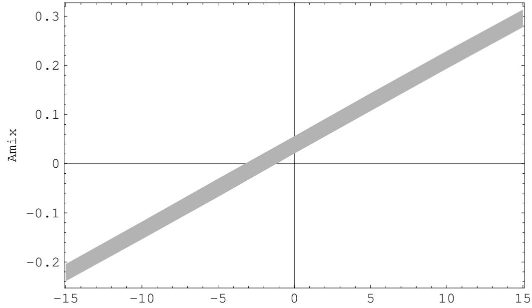

$\mathcal{A}_{\rm mix}^{\rm long}(B_s \to K^{*0}\bar{K}^{*0})$ from $B_s - \bar{B}_s$ mixing angle ϕ_s (free if NP in mixing)

$(\gamma = 62^\circ)$

Conclusions (1)

Penguin-mediated decays studied through QCD fact. and flavour sym.

- $T - P$ accurately known in QCDF and related to observables
- Test of charming penguins or determination of CKM angles

For $B_d \to K^0 \bar{K}^0$ and $B_s \to K\bar{K}$

- $Br(B_d)$ (measured) and A_{dir}^{d0} (loose range, expected ≥ 0) enough to fix tree and penguin
- Large and correlated asymmetries in $B_d \to K^0 \bar{K}^0$ and $B_s \to K^+K^-$
- Improved determination of U-spin ratios and BRs

$$
\begin{aligned}
Br(B_s \to K^+K^-)_{SM} &= (20 \pm 8 \pm 4 \pm 2) \cdot 10^{-6} \qquad \text{(OK with CDF)} \\
Br(B_s \to K^0\bar{K}^0)_{SM} &= (18 \pm 6 \pm 4 \pm 2) \cdot 10^{-6}
\end{aligned}
$$

Conclusions (2)

For $B_d \to K^{*0}\bar{K}^{*0}$ and $B_s \to K^{*0}\bar{K}^{*0}$ (longitudinal)

- Determination of ϕ_s from $\mathcal{A}_{\rm mix}$
- Correlations between Brs
- If $BR^{\rm long}(B_d \to K^{*0}\bar{K}^{*0}) \gtrsim 5 \times 10^{-7}$, good determination of P

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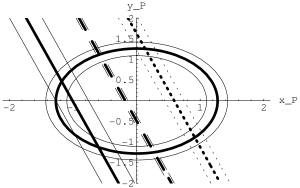
Experiment : More accurate asymmetries ? More B_s observables ?

Theory : Improved $f = \frac{M^2_{B_s} F_0^{\bar{B}_s\to K}(0)}{M^2_{B_d} F_0^{\bar{B}_d\to K}(0)}$? Other modes ?

Backup

Two-fold degeneracy in (T^{d0}, P^{d0})



Two solutions for $(T^{s\pm}, P^{s\pm})$:

- Similar $|T^{s\pm}|$ and $|P^{s\pm}/T^{s\pm}|$
- Solution used : $20^\circ \leq \arg(P^{s\pm}/T^{s\pm}) \leq 180^\circ$
- 2nd sol : $-150^\circ \leq \arg(P^{s\pm}/T^{s\pm}) \leq 20^\circ$

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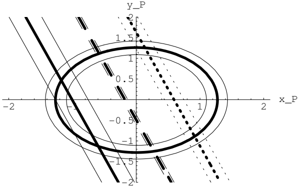

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HFAG on $B_d \to \pi^+\pi^-$ data

$$\left.\begin{array}{c} BR = (5.0 \pm 0.4) \times 10^{-6} \\ A_{dir} = -0.33 \pm 0.11 \\ A_{mix} = 0.49 \pm 0.12 \end{array}\right\} \Longrightarrow \left\{ \begin{array}{c} |T^{d\pm}_{\pi\pi}| = (5.48 \pm 0.42) \times 10^{-6} \\ \left|P^{d\pm}_{\pi\pi}/T^{d\pm}_{\pi\pi}\right| = 0.13 \pm 0.05 \\ \arg\left(P^{d\pm}_{\pi\pi}/T^{d\pm}_{\pi\pi}\right) = (131 \pm 18)^\circ \end{array}\right.$$

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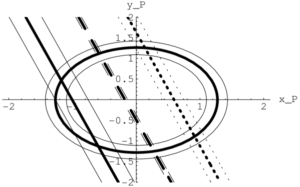

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Approximate U-spin $B_d \to \pi^+\pi^- / B_s \to K^+K^-$

- Discard 2nd sol: $\arg(P^{s\pm}/T^{s\pm})$ should be positive
- Favours sol used with $A^{d0}_{dir} > 0$

Comparing QCDF and our approach

Main uncertainties from long-distance (IR-divergent) terms

- QCD factorisation : Source of substantial errors to model

Observable	QCDF default set	QCDF S4
$BR^{s0} \times 10^6$	$24.7^{+2.5+13.7+2.6+25.6}_{-2.4-9.2-2.9-9.8}$	38.3
$A^{s0}_{dir} \times 10^2$	$0.9^{+0.2+0.2+0.1+0.2}_{-0.2-0.2-0.1-0.3}$	0.6
$BR^{s\pm} \times 10^6$	$22.7^{+3.5+12.7+2.0+24.1}_{-3.2-8.4-2.0-9.1}$	36.1
$A^{s\pm}_{dir} \times 10^2$	$4.0^{+1.0+2.0+0.5+10.4}_{-1.0-2.3-0.5-11.3}$	-4.7

Beneke and Neubert, Nucl.Phys.B675:333-415,2003

- Our approach : Extracted from other flavour-related decays

A^{d0}_{dir}	$BR^{s0} \times 10^6$	$A^{s0}_{dir} \times 10^2$	$BR^{s\pm} \times 10^6$	$A^{s\pm}_{dir} \times 10^2$
-0.2	$18.4 \pm 6.5 \pm 3.6$	0.8 ± 0.3	$21.9 \pm 7.9 \pm 4.3$	24.3 ± 18.4
-0.1	$18.2 \pm 6.4 \pm 3.6$	0.4 ± 0.3	$19.6 \pm 7.3 \pm 4.2$	35.7 ± 14.4
0	$18.1 \pm 6.3 \pm 3.6$	0 ± 0.3	$17.8 \pm 6.0 \pm 3.7$	37.0 ± 12.3
0.1	$18.2 \pm 6.4 \pm 3.6$	-0.4 ± 0.3	$16.4 \pm 5.7 \pm 3.3$	29.7 ± 19.9
0.2	$18.4 \pm 6.5 \pm 3.6$	-0.8 ± 0.3	$15.4 \pm 5.6 \pm 3.1$	6.8 ± 28.9

$A^{d0}_{dir} = -0.40 \pm 0.41 \pm 0.06$ [BaBar] $\quad BR^{s\pm} = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$ [CDF]

Comparing flavour symmetries and our approach

Quantitative statement about U-spin breaking

- Flavour symmetries : guesstimated fudge factors

$$\xi = \left|\frac{P^{s\pm}}{T^{s\pm}} \times \frac{T^{d\pm}_{\pi\pi}}{P^{d\pm}_{\pi\pi}}\right| = 1.0 \pm 0.2 \quad \text{(assumed)}$$

$$R_c = \left|\frac{T^{s\pm}}{T^{d\pm}_{\pi\pi}}\right| = 1.76 \pm 0.17 \quad \text{(sum rule)}$$

$$4.2 \cdot 10^{-6} \leq BR^{s\pm} \leq 61.9 \cdot 10^{-6}$$

S. Baek, D. London, J. Matias, J. Virto, JHEP 0602:027,2006

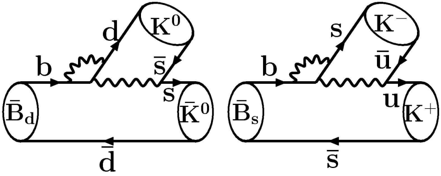
- Our approach : Estimate through QCDF analysis of U-spin relations

$$\xi = 0.8 \pm 0.4 \quad \text{(computed)}$$

$$R_c = 2.0 \pm 0.8 \quad \text{(computed)}$$

$$BR^{s\pm} = (20 \pm 8 \pm 4 \pm 2) \cdot 10^{-6}$$

$B_d \to K^0 \bar{K}^0$ and $B_s \to K^+ K^-$



U-spin and isospin

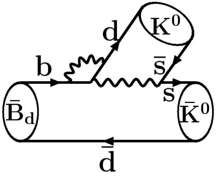
$B_s \to K^+ K^-$ penguin related to P^{d0}

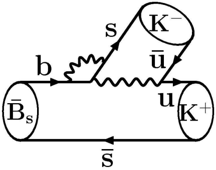
$\Longrightarrow$Most long-distance effects

are the same

QCDF bound : $\left|\frac{P^{s\pm}}{fP^{d0}} - 1\right| \leq 5\%$

$B_d \to K^0 \bar{K}^0$ and $B_s \to K^+ K^-$





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$B_s \to K^+ K^-$ penguin related to P^{d0}

$\Longrightarrow$Most long-distance effects

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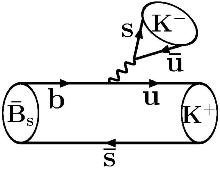
QCDF bound : $\left| \frac{P^{s\pm}}{f P^{d0}} - 1 \right| \leq 5\%$



No such simple relation for the tree part

Some related contributions but

O_1 tree contribution

to $B_s \to K^+ K^-$ unmatched

- QCDF estimate of O_1 term in $T^{s\pm}$: $\left| \frac{T^{s\pm}}{A^s_{KK} \bar{\alpha}_1} - 1 - \frac{T^{d0}}{A^d_{KK} \bar{\alpha}_1} \right| \leq 5\%$
- Cabibbo suppressed in $B_s \to K^+ K^-$

Hadronic parameters for $B_s \to K^+K^-$

Take same form factors as QCDF, and CKM factors $\lambda_p^{(q)} = V_{pb}V_{pq}^*$

$$\begin{array}{ll} \lambda_u^{(d)} = 0.0038 \cdot e^{-i\gamma} & \lambda_u^{(s)} = 0.00088 \cdot e^{-i\gamma} \\ \lambda_c^{(d)} = -0.0094 & \lambda_c^{(s)} = 0.04 \end{array} \quad \text{and } \gamma = 62^\circ$$

$B_d \to K^0\bar{K}^0$: Br, A_{dir}, $T^{d0} - P^{d0}$

$\Longrightarrow B_d \to K^0\bar{K}^0$: T^{d0} and P^{d0}

$\Longrightarrow B_s \to K^+K^-$: $T^{s\pm}$ (QCDF) and $P^{s\pm}$ (QCDF+flavour bound)

A_{dir}^{d0}	$\lvert T^{s\pm}\rvert \times 10^6$	$\lvert P^{s\pm}/T^{s\pm}\rvert$	$\arg(P^{s\pm}/T^{s\pm})$
-0.2	12.7 ± 2.8	0.09 ± 0.03	$(45 \pm 33)^\circ$
-0.1	12.1 ± 2.7	0.10 ± 0.03	$(78 \pm 27)^\circ$
0	11.5 ± 2.6	0.10 ± 0.03	$(105 \pm 15)^\circ$
0.1	11.1 ± 2.6	0.11 ± 0.03	$(137 \pm 27)^\circ$
0.2	10.8 ± 2.6	0.11 ± 0.03	$(180 \pm 10)^\circ$

Observables in $B_s \to K^+K^-$

$(P^{s\pm}, T^{s\pm})$ yields U-spin breaking between $\bar{B}_s \to K^+K^-$ and $\bar{B}_d \to \pi^+\pi^-$

$$\xi = \left| \frac{P^{s\pm}}{T^{s\pm}} \frac{T^{d\pm}_{\pi\pi}}{P^{d\pm}_{\pi\pi}} \right| = 0.8 \pm 0.4$$

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- U-spin on $B_d \to \pi^+\pi^-$: $A^{s\pm}_{mix} < 0$ and $\arg \frac{P^{s\pm}}{T^{s\pm}} \simeq 130^\circ \Longrightarrow A^{d0}_{dir} \geq 0$
- QCDF alone : $A^{d0}_{dir} \simeq 20\%$
- Babar : $A^{d0}_{dir} = -0.40 \pm 0.41 \pm 0.06$ [hep-ex/0608036]
  Belle : $A^{d0}_{dir} = 0.57^{+0.65}_{-0.72} \pm 0.13$ [hep-ex/0608049]

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CDF measurement [Beauty 2006]: $BR^{s\pm} = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$