QCD factorisation and flavour symmetries illustrated in $B_{d,s} \to KK$ decays

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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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- Good : Global symmetries of QCD, long- and short-distances
- Bad : Potentially large corrections, e.g. $SU(3)$ symmetry $O(30\%)$

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Idea : Combine them to to extract stringent SM correlations
Illustration : $B_d \to K^0\bar{K}^0$ and $B_s \to KK$

SDG, J. Matias and J. Virto, Phys.Rev.Lett.97:061801,2006

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

Conventional tree and penguin decomposition

$$\bar{A} \equiv A(\bar{B}_q \to K^0\bar{K}^0) = V_{ub}V_{uq}^* T^{q0} + V_{cb}V_{cq}^* P^{q0}$$
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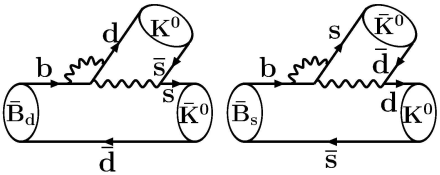

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no contribution from O_1 and O_2

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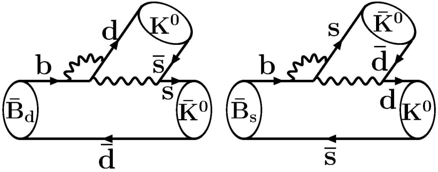

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Difference between tree and penguin from the u, c quark in loop

$\Longrightarrow T^{q0} - P^{q0}$ dominated by short-distance physics computed fairly accurately within QCDF

$$T^{d0} - P^{d0} = (1.09 \pm 0.43) \cdot 10^{-7} + i(-3.02 \pm 0.97) \cdot 10^{-7}\mathrm{GeV}$$
$$T^{s0} - P^{s0} = (1.03 \pm 0.41) \cdot 10^{-7} + i(-2.85 \pm 0.93) \cdot 10^{-7}\mathrm{GeV}$$

$T - P$: A sum rule for $B_d \to K^0 \bar{K}^0$ observables

$$\frac{\Gamma(B_d(t) \to K\bar{K}) - \Gamma(\bar{B}_d(t) \to K\bar{K})}{\Gamma(B_d(t) \to K\bar{K}) + \Gamma(\bar{B}_d(t) \to K\bar{K})} = \frac{A_{dir}^{d0} \cos(\Delta M \cdot t) + A_{mix}^{d0} \sin(\Delta M \cdot t)}{\cosh(\Delta\Gamma_d t/2) - A_{\Delta}^{d0} \sinh(\Delta\Gamma_d t/2)}$$

with CP asymmetries
$$\left\{ \begin{array}{c} A_{dir}^{d0} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}, A_{\Delta}^{d0} + iA_{mix}^{d0} = -\frac{2e^{-i\phi_d} A^* \bar{A}}{|A|^2 + |\bar{A}|^2} \\ |A_{\Delta}^{d0}|^2 + |A_{dir}^{d0}|^2 + |A_{mix}^{d0}|^2 = 1 \end{array} \right.$$

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$$|T^{d0} - P^{d0}|^2 = \frac{BR^{d0}\times 32\pi M_{Bd}^2}{\tau_d\sqrt{M_{Bd}^2-4M_K^2}}$$
$$\times\{x_1 + [x_2\sin\phi_d - x_3\cos\phi_d]A_{mix}^{d0} - [x_2\cos\phi_d + x_3\sin\phi_d]A_{\Delta}^{d0}\}$$

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- SM consistency test between BR^{d0}, $|A_{dir}^{d0}|$ and A_{mix}^{d0} (id. for B_s)
- SM value of one (say $|A_{mix}^{d0}|$) from the two others (BR^{d0} and A_{dir}^{d0})
- Determination of γ (A. Datta et al. hep-ph/0611280)

$T - P$: 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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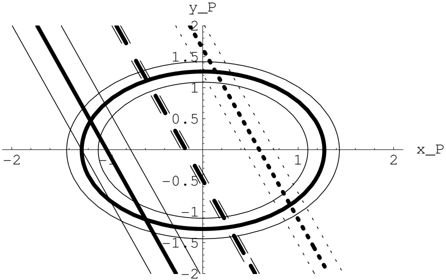


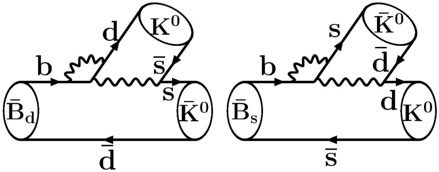
$$P = (x_P + iy_P) \cdot 10^{-6}\ \text{GeV}$$

- $Br + (T-P) \Longrightarrow$ 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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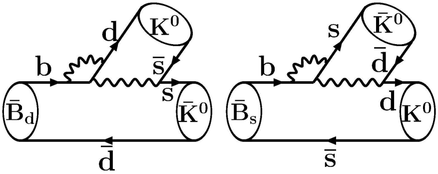

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U-spin breaking only in a few places :

- 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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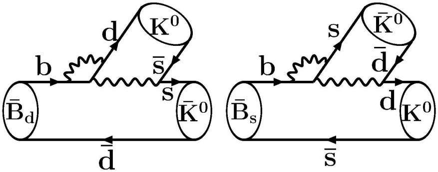

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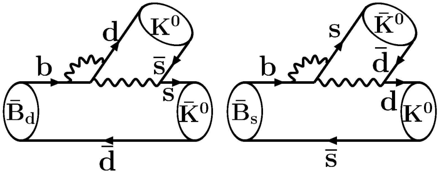

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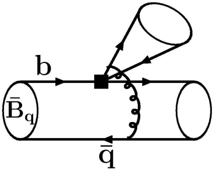
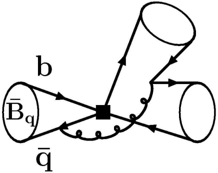


Hard-spectator scattering
(B_d and B_s distribution amplitudes)



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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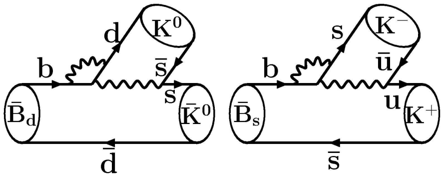
U-spin breaking in very few places

- 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

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

$B_d \to K^0 \bar{K}^0$ 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

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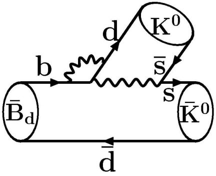

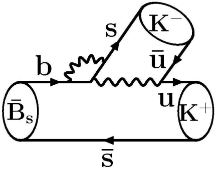

U-spin and isospin
$B_s \to K^+ K^-$ penguin related to P^{d0}
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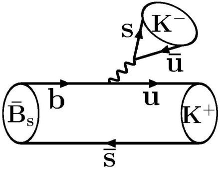

No such simple relation for the tree part
Some related contributions but
O_1 tree contribution
to $B_s \to K^+ K^-$ unmatched

- 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 $\lambda_p^{(q)} = V_{pb}V_{pq}^*$

$$\lambda_u^{(d)} = 0.0038 \cdot e^{-i\gamma} \quad \lambda_u^{(s)} = 0.00088 \cdot e^{-i\gamma}$$
$$\lambda_c^{(d)} = -0.0094 \quad \lambda_c^{(s)} = 0.04$$

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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A^{d0}_{dir}	$BR^{s\pm} \times 10^6$	$A^{s\pm}_{dir} \times 10^2$	$A^{s\pm}_{mix} \times 10^2$
-0.2	$21.9 \pm 7.9 \pm 4.3$	24.3 ± 18.4	24.7 ± 15.5
-0.1	$19.6 \pm 7.3 \pm 4.2$	35.7 ± 14.4	7.7 ± 15.7
0	$17.8 \pm 6.0 \pm 3.7$	37.0 ± 12.3	-9.3 ± 10.6
0.1	$16.4 \pm 5.7 \pm 3.3$	29.7 ± 19.9	-26.3 ± 15.6
0.2	$15.4 \pm 5.6 \pm 3.1$	6.8 ± 28.9	-40.2 ± 14.6

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

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

$\Longrightarrow B_s \to K^+ K^-$: T^{s0} and P^{s0} (QCDF+flavour bounds)

A^{d0}_{dir}	$BR^{s0} \times 10^6$	$A^{s0}_{dir} \times 10^2$	$A^{s0}_{mix} \times 10^2$
-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
0	$18.1 \pm 6.3 \pm 3.6$	0 ± 0.3	-0.8 ± 0.7
0.1	$18.2 \pm 6.4 \pm 3.6$	-0.4 ± 0.3	-0.7 ± 0.7
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- Very small asymmetries, but BR very stable within SM
- $1/m_b$-suppressed contributions : No specific model (à la QCDF) but relations between B_d and B_s decays
- All constraints derived from SM relation between $b \to d$ and $b \to s$ and should be upset by New Physics

Conclusion

- Better understanding of B-decays by combining QCD factorisation and flavour symmetries : $B_d \to K^0\bar{K}^0$ related to $B_s \to K\bar{K}$
- $T^{d0} - P^{d0}$ accurately known in QCDF and related to observables
- $Br(B_d \to K^0\bar{K}^0)$ (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
- Clean SM predictions (improvable with f and A_{dir}^{d0})

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

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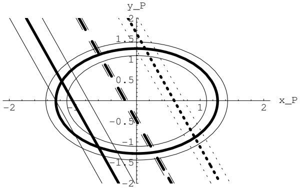
Experiment : More accurate A_{dir}^{d0} ? More B_s observables ?

Theory : Improved $f = \frac{M_{B_s}^2 F_0^{\bar{B}_s \to K}(0)}{[M_{B_d}^2 F_0^{\bar{B}_d \to K}(0)]}$? Application to 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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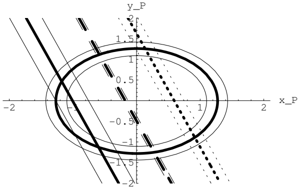

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HFAG on $B_d \to \pi^+\pi^-$ data

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

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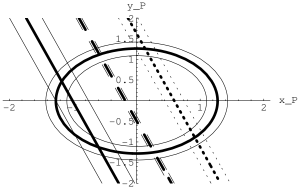

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Approximate U-spin $B_d \to \pi^+\pi^- / B_s \to K^+K^-$

- 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

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

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

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

Dependence on γ

- Almost no dependence of predictions for CP asymmetries in $B_s \to K\bar{K}^0$ and mixed asymmetry in $B_s \to K^+K^-$
- A limited sensitivity of order 10% for the other observables, e.g. if we take $A_{dir}^{d0} = 0$

Observable	$\gamma = 62^\circ$	$\gamma = 68^\circ$
$BR^{s0} \times 10^6$	$18.1 \pm 6.3 \pm 3.6$	$17.0 \pm 5.9 \pm 3.6$
$BR^{s\pm} \times 10^6$	$17.8 \pm 6.0 \pm 3.6$	$17.1 \pm 5.8 \pm 3.6$
$A_{dir}^{s\pm} \times 10^2$	37.0 ± 12.3	40.5 ± 12.5