

Final State Interactions in Hadronic B Decays

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Large energy release in B decays \Rightarrow minor role for FSIs ?

Several possible hints at large FSI effects in B physics:

- Some decay modes do not receive factorizable contributions
e.g. $B \rightarrow K\chi_{0c}$ with $BR=(2-6)\times 10^{-6}$, though $\langle \chi_{0c} | c\gamma_{\mu}(1-\gamma_5)c | 0 \rangle = 0$.
- Color-suppressed $B^0 \rightarrow D^0 h^0$ ($h^0 = \pi^0, \omega, \rho^0, \eta, \eta'$) measured by Belle, CLEO, BaBar are larger than theoretical expectations.
- $Br(B^0 \rightarrow \pi^0\pi^0) \sim 2 \times 10^{-6}$ cannot be explained by QCDF or pQCD.
Likewise, $Br(B^0 \rightarrow \rho^0\pi^0) = (5.1 \pm 1.6 \pm 0.9) \times 10^{-6}$ measured by Belle is much higher than theoretical expectation.
- Direct CPV in $B^0 \rightarrow K^+\pi^-$ is established by BaBar and Belle. QCDF predicts a wrong sign. Likewise for $B^0 \rightarrow \pi^+\pi^-$.

■ $B^0 \rightarrow D_s^- K^+$ proceeds only via W -exchange. Its sizable BR of order 4×10^{-5} observed by Belle and BaBar seems to indicate a large final-state rescattering.

■ Longitudinal fraction $f_L \approx 50\%$ for $B \rightarrow \phi K^*$ by Belle & BaBar
 \Rightarrow in sharp contrast to the scaling law:

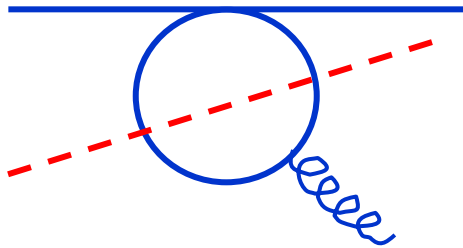
$$1 - f_L = O(1/m_b^2)$$

for factorizable amplitudes in B decays to light vector mesons,
e.g. $B \rightarrow \rho\rho$. \Rightarrow rescattering effect or new physics ?

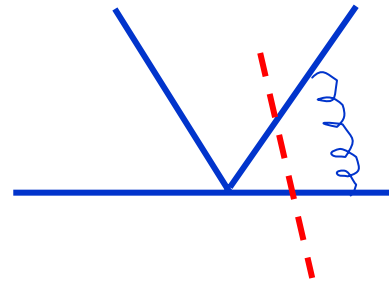
FSI has a more profound impact on direct CP violation

CP asymmetry $\propto \sin\phi \sin\delta$ δ : weak phase, ϕ : strong phase

- “Simple” CP violation from perturbative strong phases:

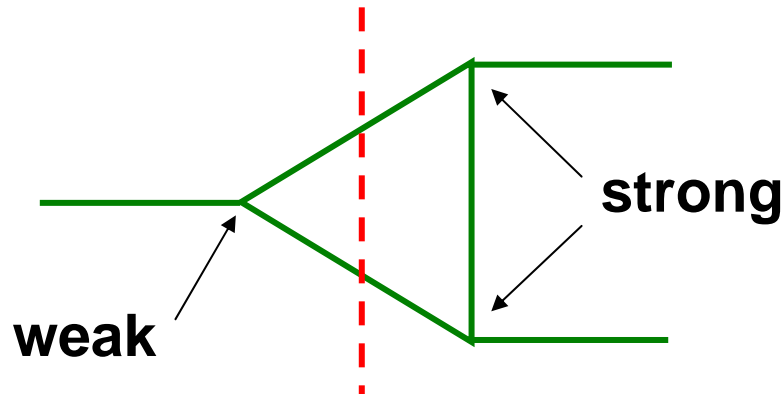


penguin (Bander, Silverman, Soni)

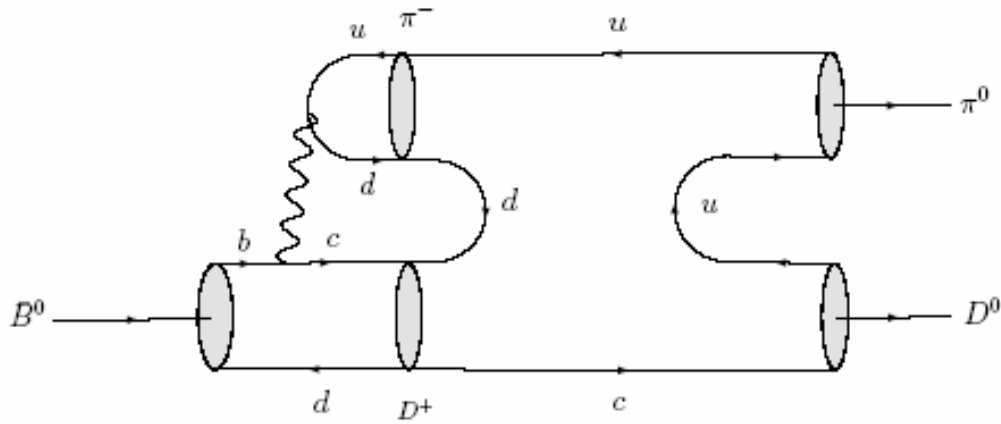


vertex corrections (BBNS)

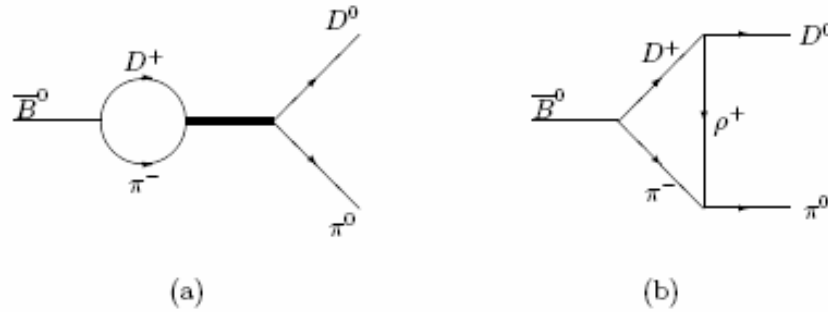
- “Compound” CP violation from LD rescattering: [Atwood, Soni]



quark level:

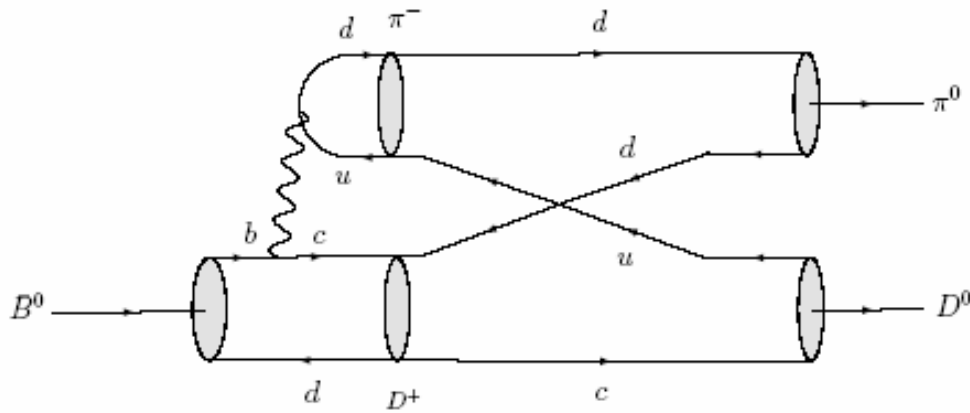


hadron level :

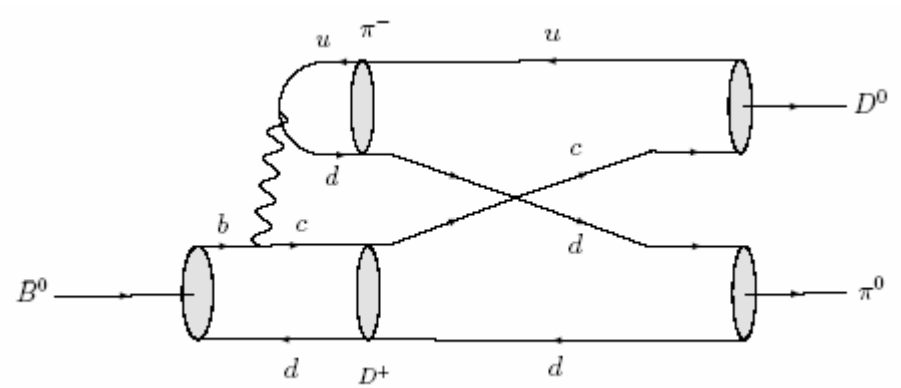
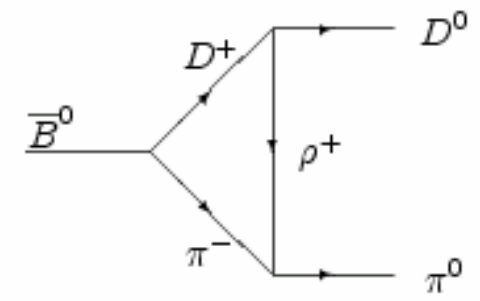


(a) s-channel with $J^P=0^+$ resonance

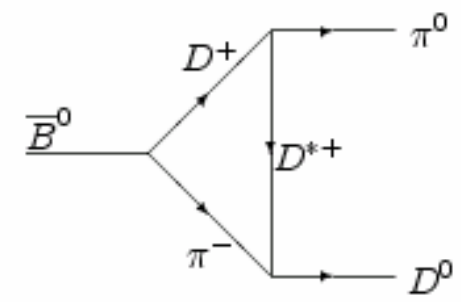
(b) t-channel with one particle exchange



\Rightarrow



\Rightarrow

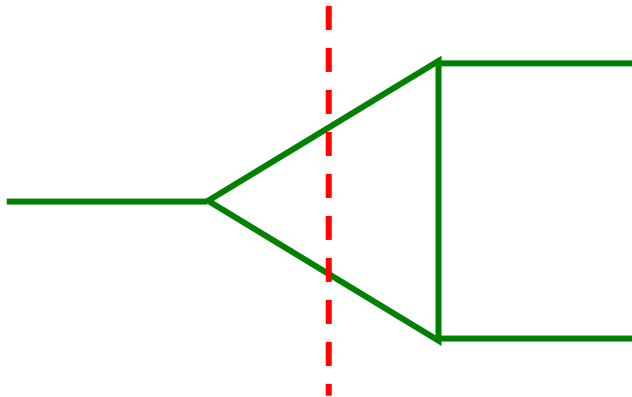


At hadron level, FSIs manifest as resonant s-channel and triangular t-channel graphs.

However, FSIs via resonances are suppressed in B decays due to the lack of resonances at energies close to B mass.

For t-channel contributions, absorptive part is computed via optical theorem: weak decay followed by strong rescattering

$$2\Im m M(B \rightarrow f) = \sum_i M(B \rightarrow i) T_{if}^*$$



- Strong coupling is fixed on shell
- Cutoff must be introduced as exchanged particle is off-shell

$$F(t) = \frac{1 - (m^2 / \Lambda^2)}{1 - (t / \Lambda^2)}$$

Dispersive part is obtained from the absorptive amplitude via dispersion relation

$$\Re M(m_B^2) = \frac{1}{\pi} \int_s^\infty \frac{\Im m M(s')}{s' - m_B^2} ds'$$

B \rightarrow D π Decays

Color-suppressed $B^0 \rightarrow D^{(*)0} h^0$ ($h = \pi, \omega, \rho, \eta, \eta'$) have been observed with BRs of order 1.7×10^{-4} to 4.2×10^{-4} , larger than theoretical expectations.

For example, NF \Rightarrow $\text{BR}(B^0 \rightarrow D^0 \pi^0) = (0.6 \sim 1.1) \times 10^{-4}$, too small by a factor of $3 \sim 5$ compared to the measured BR, 2.9×10^{-4} .

The decay amplitudes

$$A(\bar{B}^0 \rightarrow D^+ \pi^-) = T + E$$

$$A(B^- \rightarrow D^0 \pi^-) = T + C$$

$$A(\bar{B}^0 \rightarrow D^0 \pi^0) = \frac{1}{\sqrt{2}}(-C + E)$$

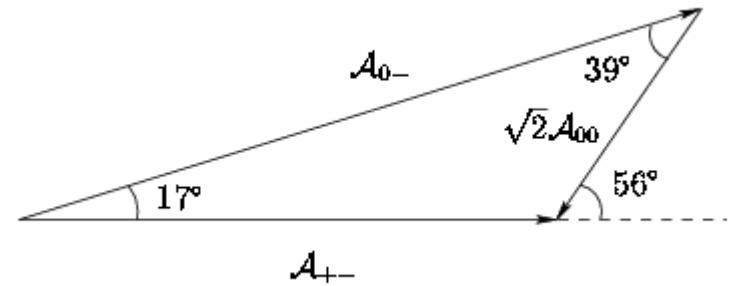
satisfy the isospin triangular relation

$$A(\bar{B}^0 \rightarrow D^+ \pi^-) = \sqrt{2} A(\bar{B}^0 \rightarrow D^0 \pi^0) + A(B^- \rightarrow D^- \pi^0)$$

Experimental data of $B \rightarrow D\pi$ imply that

$$\left. \frac{C - E}{T + E} \right|_{D\pi} = (0.46 \pm 0.05) e^{\pm i 61^\circ},$$

$$\left. \frac{C - E}{T + C} \right|_{D\pi} = (0.36 \pm 0.03) e^{\pm i 43^\circ}$$



Neglecting weak annihilation $E \Rightarrow a_2/a_1 \approx (0.4 \sim 0.5) \exp[\pm i 59^\circ]$,
in contrast to NF expectation of $|a_2/a_1| \approx (0.2 \sim 0.3)$.

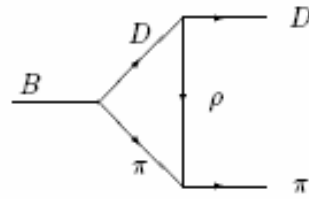
Remarks: \blacklozenge $|a_2/a_1| = (0.26 \pm 0.02)$ inferred from $B \rightarrow J/\psi K$ [HYC, Yang]

\blacklozenge a_2 is not calculable for $B \rightarrow D\pi$ in QCDF

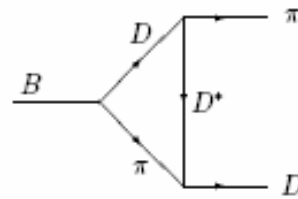
Puzzle: Why is that a_2/a_1 has large magnitude and strong phase in
 $B \rightarrow D\pi$ decays ?

[Xing; Neubert, Petrov; HYC; Lee]

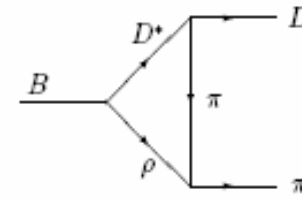
Long-distance contributions to $B \rightarrow D \pi$



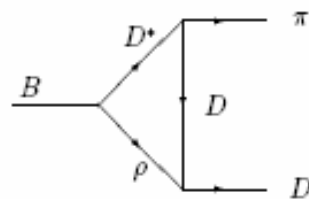
(a)



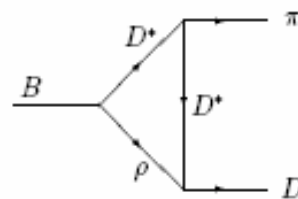
(b)



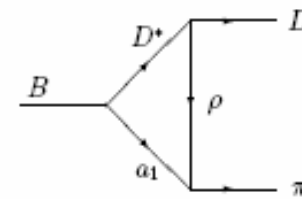
(c)



(d)



(e)



(f)

$$T = T_{SD},$$

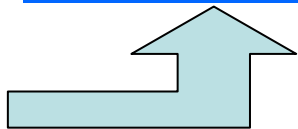
$$C = C_{SD} + iAbs(a + b + c + d + e + f),$$

$$E = E_{SD} + iAbs(a + c + f)$$

	without FSI	with FSI	Expt
$Br(\bar{B}^0 \rightarrow D^+ \pi^-) = 3.2 \times 10^{-3}$		3.1×10^{-3}	$(2.76 \pm 0.25) \times 10^{-3}$
$Br(B^- \rightarrow D^0 \pi^-) = 4.9 \times 10^{-3}$		$5.0_{-0.1}^{+0.2} \times 10^{-3}$	$(4.98 \pm 0.29) \times 10^{-3}$
$Br(\bar{B}^0 \rightarrow D^0 \pi^0) = 0.6 \times 10^{-4}$		$2.7_{-1.3}^{+2.3} \times 10^{-4}$	$(2.9 \pm 0.2) \times 10^{-4}$

For $a_1=0.95$, $a_2=0.25$

Even if short-distance W-exchange vanishes, final-state rescattering will contribute to weak annihilation



$$\frac{C}{T} = 0.20 \rightarrow 0.30 e^{-i50^\circ}$$

$$\frac{E}{T} = 0 \rightarrow 0.14 e^{-i84^\circ}$$

$$\frac{C-E}{T+E} = 0.20 \rightarrow 0.43 e^{-i69^\circ}$$

$$\frac{C-E}{T+C} = 0.17 \rightarrow 0.35 e^{-i50^\circ}$$

in agreement

with expt.

$$\frac{C-E}{T+E} = (0.46 \pm 0.05) e^{\pm i61^\circ},$$

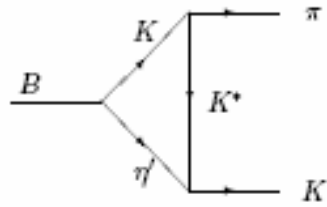
$$\frac{C-E}{T+C} = (0.36 \pm 0.03) e^{\pm i43^\circ}$$

B → π K

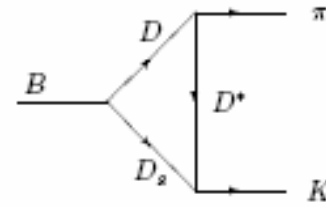
	BR	A
$\bar{B}^0 \rightarrow \pi^+ K^-$	$(18.2 \pm 0.8) 10^{-6}$	<u>-0.11 ± 0.02</u>
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^0$	$(11.7 \pm 1.4) 10^{-6}$	-0.19 ± 0.14
$B^- \rightarrow \pi^- \bar{K}^0$	$(24.1 \pm 1.3) 10^{-6}$	-0.02 ± 0.03
$B^- \rightarrow \pi^0 K^-$	$(12.1 \pm 0.8) 10^{-6}$	0.04 ± 0.04

First evidence of direct CPV in $B^0 \rightarrow K^+ \pi^-$ at 4.2σ was reported by BaBar, confirmed by Belle at 3.9σ .

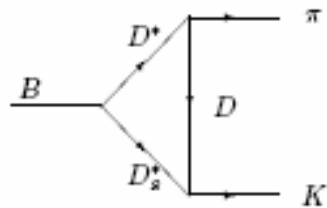
	QCDF	pQCD
$Br(\bar{B}^0 \rightarrow \pi^+ K^-)_{SD} = 13.9 \times 10^{-6}$	$A_{SD} = 0.04$	<u>$-(0.13 - 0.22)$</u>
$Br(\bar{B}^0 \rightarrow \pi^0 \bar{K}^0)_{SD} = 6.3 \times 10^{-6}$	$A_{SD} = -0.04$	
$Br(B^- \rightarrow \pi^- \bar{K}^0)_{SD} = 17.8 \times 10^{-6}$	$A_{SD} = 0.009$	$-(0.10 - 0.17)$
$Br(B^- \rightarrow \pi^0 K^-)_{SD} = 9.7 \times 10^{-6}$	$A_{SD} = 0.07$	$-(0.01 - 0.02)$



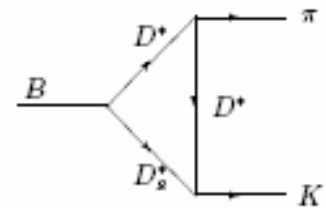
(a)



(b)



(c)



(d)

$$C = C_{SD} + iAbs(a)$$

$$E = E_{CD} + i\frac{1}{2}Abs(a)$$

$$P = P_{SD} + i\frac{1}{2}Abs(a + 2b + 2c + 2d)$$

	BR SD (10^{-6})	BR with FSI (10^{-6})	BR Expt (10^{-6})	CPV SD	CPV with FSI	CPV Expt
$B^- \rightarrow \pi^- K^0$	17.8	$21.1^{+41.5}_{-3.6}$	24.1 ± 1.3	0.01	$0.024^{+0.001}_{-0.013}$	-0.02 ± 0.03
$B^0 \rightarrow \pi^+ K^-$	13.9	$17.2^{+38.9}_{-3.6}$	18.2 ± 0.8	0.04	$-0.13^{+0.01}_{-0.15}$	-0.11 ± 0.02
$B^- \rightarrow \pi^0 K^-$	9.7	$11.4^{+20.8}_{-1.8}$	12.1 ± 0.8	0.08	$-0.09^{+0.05}_{-0.16}$	0.04 ± 0.04
$B^0 \rightarrow \pi^0 K^0$	6.3	$8.0^{+19.5}_{-1.8}$	11.7 ± 1.4	-0.04	$0.02^{+0.02}_{-0.06}$	-0.09 ± 0.14

- ◆ Sign of $\pi^+ K^-$ CP asymmetry is flipped after rescattering and is in agreement with experiment.
- ◆ The rate of $\pi^0 K^0$ is still slightly smaller than experiment. Same difficulty occurs in a global fit to charmless B decay data using topological approach. [Chiang et al.]

B → π π

	BR	A	S
$\bar{B}^0 \rightarrow \pi^+ \pi^-$	$(4.6 \pm 0.4) 10^{-6}$	<u>0.32 ± 0.11</u>	-0.56 ± 0.13
$\bar{B}^0 \rightarrow \pi^0 \pi^0$	$(1.5 \pm 0.3) 10^{-6}$	-0.17 ± 0.39	
$B^- \rightarrow \pi^- \pi^0$	$(5.5 \pm 0.6) 10^{-6}$	-0.02 ± 0.14	

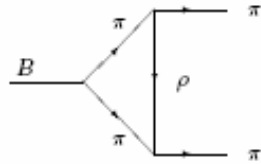
$$\frac{\Gamma(\bar{B}(t) \rightarrow \bar{f}) - \Gamma(B(t) \rightarrow f)}{\Gamma(\bar{B}(t) \rightarrow \bar{f}) + \Gamma(B(t) \rightarrow f)} = S_f \sin(\Delta m t) - C_f \cos(\Delta m t),$$

$A_f = -C_f$: direct CP asymmetry; S_f : mixing-induced CP violation

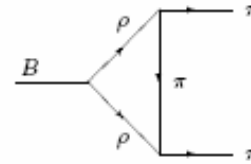
Belle claimed evidence of direct CP violation in $B^0 \rightarrow \pi^+ \pi^-$ at 5.2σ , but not confirmed by BaBar.

	QCDF	pQCD
$Br(\bar{B}^0 \rightarrow \pi^+ \pi^-)_{SD} = 7.6 \times 10^{-6}$	$A_{SD} = -0.05$	<u>$0.16 - 0.30$</u>
$Br(\bar{B}^0 \rightarrow \pi^0 \pi^0)_{SD} = 0.3 \times 10^{-6}$	$A_{SD} = 0.61$	$0.10 - 0.20$
$Br(B^- \rightarrow \pi^- \pi^0)_{SD} = 5.1 \times 10^{-6}$	$A_{SD} = 5 \times 10^{-5}$	0

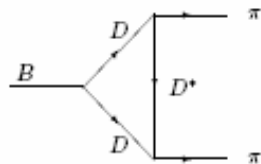
Long-distance contributions to $B \rightarrow \pi \pi$



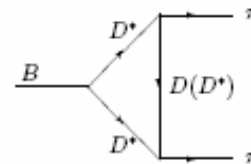
(a)



(b)



(c)



(d),(e)

$$C = C_{SD} + iAbs(a + b)$$

$$E = E_{CD} + i\frac{1}{2}Abs(a + b)$$

$$P = P_{SD} + i\frac{1}{2}Abs(a + b + 2c + 2d + 2e)$$

$B^- \rightarrow \pi^- \pi^0$ receives contributions from (a) and (b) only

satisfy the isospin relation

$$A(\bar{B}^0 \rightarrow \pi^+ \pi^-) = \sqrt{2} \left[A(\bar{B}^0 \rightarrow \pi^0 \pi^0) + A(B^- \rightarrow \pi^- \pi^0) \right]$$

	BR SD (10^{-6})	BR with FSI (10^{-6})	BR Expt (10^{-6})	CPV SD	CPV with FSI	CPV Expt
$B^0 \rightarrow \pi^+ \pi^-$	7.6	$11.5^{+8.1}_{-3.1}$	4.6 ± 0.4	-0.05	$0.55^{+0.07}_{-0.29}$	0.31 ± 0.11
$B^0 \rightarrow \pi^0 \pi^0$	0.3	$1.5^{+3.3}_{-1.1}$	1.5 ± 0.3	0.61	$-0.63^{+0.09}_{-0.24}$	-0.17 ± 0.39
$B^- \rightarrow \pi^- \pi^0$	5.1	5.5 ± 0.1	5.5 ± 0.6	5×10^{-5}	-0.006 ± 0.002	-0.02 ± 0.14

- Sign of direct CP asymmetry is flipped after rescattering !
- The $\pi^+ \pi^-$ rate is still too large by a factor of 2 \Rightarrow It is very likely that dispersive contribution interferes destructively with SD amplitude.
- CPV in $\pi^- \pi^0$ mode is approximately null. It provides a nice test of SM and New Physics

B \rightarrow $\rho\pi$

	BR SD (10^{-6})	BR with FSI (10^{-6})	BR Expt (10^{-6})	CPV SD	CPV with FSI	CPV Expt
$\bar{B}^0 \rightarrow \rho^+\pi^-$	7.9	$8.4^{+0.1}_0$	} 24.0 ± 2.5	-0.01	$-0.42^{+0.23}_{-0.21}$	-0.48 ± 0.14
$\bar{B}^0 \rightarrow \rho^-\pi^+$	18.4	$18.8^{+0.1}_{-0}$		-0.03	$-0.23^{+0.14}_{-0.10}$	-0.15 ± 0.09
$\bar{B}^0 \rightarrow \rho^0\pi^0$	0.6	$1.2^{+0.9}_{-0.4}$	5.1 ± 1.8	0.01	$0.55^{+0.0}_{-0.18}$	
$B^- \rightarrow \rho^-\pi^0$	12.8	$13.7^{+1.5}_{-0.6}$	12.0 ± 1.9	-0.04	$0.33^{+0.21}_{-0.19}$	0.16 ± 0.13
$B^- \rightarrow \rho^0\pi^-$	6.8	$7.2^{+1.2}_{-0.4}$	$9.2^{+1.2}_{-1.1}$	0.06	$-0.47^{+0.29}_{-0.30}$	-0.19 ± 0.11

- Direct CPV in $\rho^+\pi^-$ mode is 3.6σ from 0, well accounted for.
- $\rho^0\pi^0$ mode is of order 1.2×10^{-6} , consistent with BaBar upper limit, 2.9×10^{-6} , but too small compared to Belle result of $(5.1 \pm 1.8) \times 10^{-6}$
- We use $F_1^{B\rho}(0) = 0.30$ [HYC, Chua, Hwang]. If $F_1^{B\rho}(0) = 0.37$ is employed, the $\rho^\pm\pi^\mp$ will become too large

Polarization anomaly in $B \rightarrow \phi K^*, \rho K^*$

Short-distance induced transverse polarization in $B \rightarrow V_1 V_2$ (V: light vector meson) is expected to be suppressed

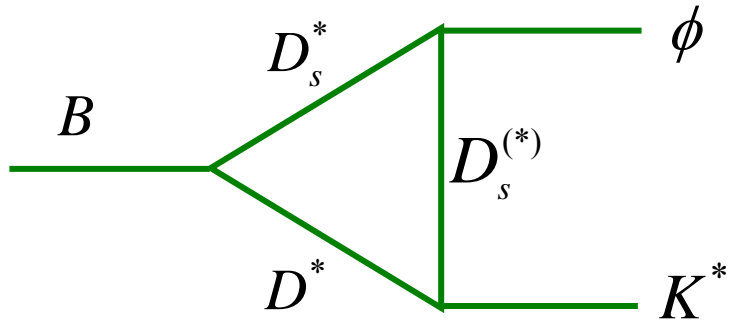
$$\text{scaling law : } 1 - f_L = O(1/m_b^2)$$

is respected by $B \rightarrow \rho\rho$, but not by ϕK^* mode,

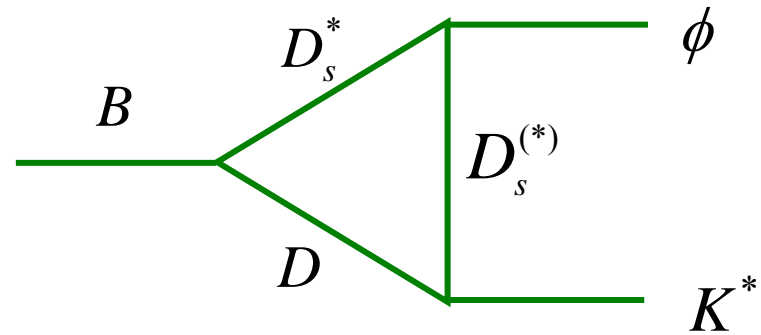
$f_L(\phi K^*) \sim 1/2 \Rightarrow \phi K^*$ polarization anomaly ! new physics ?

Kagan: Anomaly can be accommodated by large penguin induced annihilation

One idea: Get large transverse polarization from $B \rightarrow D_s^* D^*$ ($f_L \sim 0.50$!) to circumvent scaling rule at short distances and then convey it to ϕK^* via final-state rescattering



$$f_L(D_s^* D^*) \sim 0.50$$



contributes to A_\perp only

We found large cancellation occurs in $B \rightarrow \{ D_s^* D, D_s D^* \} \rightarrow \phi K^*$ processes, which can be understood as CP and SU(3) symmetry

\Rightarrow No sizable transverse polarization induced from this subset of rescattering !

in sharp contrast to the claim made by Colangelo, De Fazio, Pham, (hep-ph/0406162)

Conclusion

- ◆ **Color-suppressed modes such as $B^0 \rightarrow D^0 \pi^0, \pi^0 \pi^0, \rho^0 \pi^0, \dots$ are substantially enhanced by LD rescattering.**
- ◆ **CPV in $K^- \pi^+$ and $\pi^+ \pi^-$ predicted by QCDF are too small and in wrong sign. Correct sign and right magnitude are obtained after the inclusion of FSI.**

- ◆ **Polarization anomaly cannot be explained by rescattering**

$$B \rightarrow D^{(*)} D_s^{(*)} \rightarrow \phi K^* \quad \text{as large cancellation occurs in}$$

$$B \rightarrow \{VP, PV\} \rightarrow \phi K^*.$$