THE PUZZLING B → PP DECAYS

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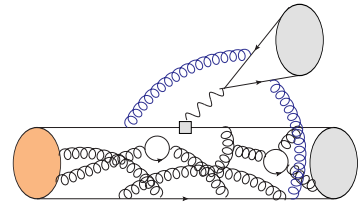
$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V_{pd}^* \left\{ C_1(\mu)\mathcal{O}_1^p + C_2(\mu)\mathcal{O}_2^p + \sum_{i=3,..,10} C_i(\mu)\mathcal{O}_i + C_{7\gamma}\mathcal{O}_{7\gamma} + C_{8g}\mathcal{O}_{8g} \right\}$$

$$|A|e^{i\delta} \sim \langle \overline{f}|\mathcal{H}_{weak}|\overline{B}\rangle = \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle \overline{f}|\mathcal{O}_k(\mu)|\overline{B}\rangle}_{\text{non-pert. QCD}}$$



CALCULATION OF $|A|e^{i\delta}$:

- use of FLAVOUR (isospin, SU(3)) symmetries [Gronau, Rosner et. al]
- QCD factorization [Beneke, Buchalla, Neubert, Sachrajda (1999)]

$$\langle M_1 M_2|\mathcal{O}_i|B\rangle = \int d\omega du dv \phi_B(\omega) T_H^i(\omega, u, v)\phi_{M_1}(u)\phi_{M_2}(v)$$

- PQCD approach [Keum, Sanda, Li (2001)]

$$\langle M_1 M_2|\mathcal{O}_i|B\rangle = \int dk_{\perp_i} d\omega du dv \phi_B(\omega, k_{\perp_3}) T_H^i(\omega, u, v, k_{\perp_i})\phi_{M_1}(u, k_{\perp_1})\phi_{M_2}(v, k_{\perp_2})$$

- **LIGHT-CONE SUM RULE METHOD** [Khodjamirian (2001)]

$$\langle \bar{f}|\mathcal{O}_k(\mu)|\overline{B}\rangle \sim \langle \pi\pi|\mathcal{O}_1|B\rangle \quad = \quad \underbrace{\langle \pi|\bar{d}\Gamma_\mu u|0\rangle \langle \pi|\bar{u}\Gamma^\mu b|B\rangle}_{\text{'naive' factorization}} \Big[1 + O(\alpha_s, \Lambda_{QCD}/m_b)\Big] = i m_b^2 f_\pi f^+_{B\pi}(m_\pi^2)\Big[1 + O(\alpha_s, \frac{\Lambda_{QCD}}{m_b})\Big]$$

$B \to P$ TRANSITION FORM FACTORS FROM LCSR:

$$f^+_{B\pi}(0) = f^0_{B\pi}(0) = 0.26^{+0.04}_{-0.03} \qquad f^T_{B\pi}(0) = 0.255 \pm 0.035$$

[G. Duplančić, A. Khodjamirian, Th. Mannel, B.M., N. Offen (2008)]

- extraction of the $|V_{ub}|$ matrix element from exclusive B decays:

  exp. $|V_{ub}|$ $f^+_{B\pi}(0) \Rightarrow |V_{ub}| = (3.5 \pm 0.4 \pm 0.2 \pm 0.1) \times 10^3$

SU(3) BREAKING

$$\Delta_{SU(3)} \sim \quad (\, f_K/f_\pi \,,\, f_{BK}/f_{B\pi} \,,\, m_s \ldots \,)$$

- $B \to K$ form factors

$$f^+_{BK}(0) = f^0_{BK}(0) = 0.36^{+0.05}_{-0.04}\,,$$
$$f^T_{BK}(0) = 0.38 \pm 0.05$$

- $B_s \to K$ form factors

$$f^+_{B_sK}(0) = f^0_{B_sK}(0) = 0.30^{+0.04}_{-0.03}\,,$$
$$f^T_{B_sK}(0) = 0.30 \pm 0.05$$

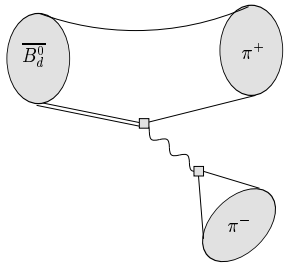
[G. Duplančić, B.M.(2008)]

- predicted SU(3) breaking:

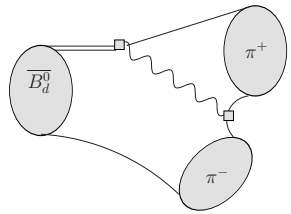
$$\frac{f^+_{BK}(0)}{f^+_{B\pi}(0)} = 1.38^{+0.11}_{-0.10}\,, \qquad \frac{f^+_{B_sK}(0)}{f^+_{B\pi}(0)} = 1.15^{+0.17}_{-0.09}\,, \qquad \frac{f^T_{BK}(0)}{f^T_{B\pi}(0)} = 1.49^{+0.18}_{-0.06}\,, \qquad \frac{f^T_{B_sK}(0)}{f^T_{B\pi}(0)} = 1.17^{+0.15}_{-0.11}$$

$$\frac{A_{fact}(B_s \to K^+K^-)}{A_{fact}(B_d \to \pi^+\pi^-)} = \frac{f_K}{f_\pi}\frac{f^+_{B_sK}(m_K^2)}{f^+_{B\pi}(m_\pi^2)}\frac{m_{B_s}^2 - m_K^2}{m_B^2 - m_\pi^2} = 1.41^{+0.20}_{-0.11}$$

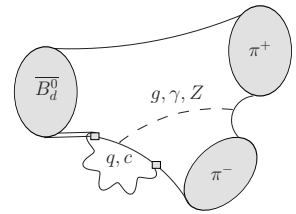
DIFFERENT TOPOLOGIES CONTRIBUTING:



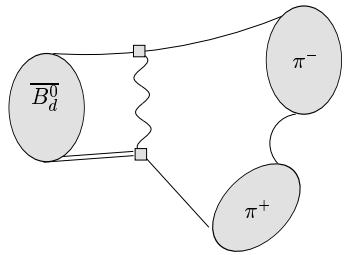
(a) emission - T



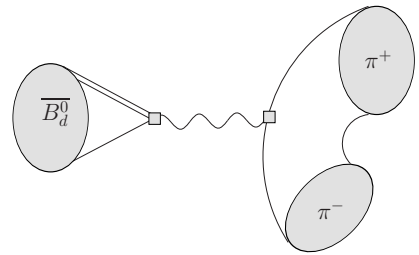
(b) emission - C



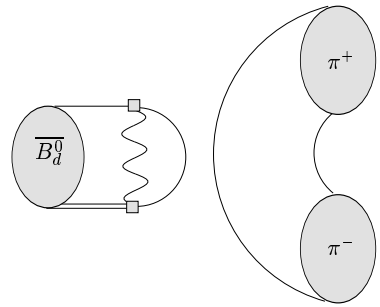
(c) penguin - $P_{q,c}$, P_{EW}^{C}



(d) annihilation - E

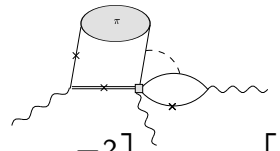
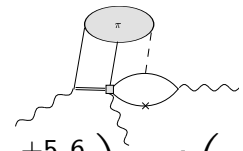


(e) annihilation - A



(f) penguin annihilation - PA,PE

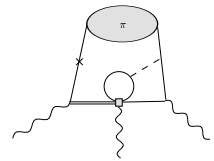
▷ EMISSION TOPOLOGY - nonfactorizable $O(\Lambda/m_b)$ corrections from $\tilde{\mathcal{O}}_1 = (\bar{d}\Gamma_\mu \frac{\lambda^a}{2} u)(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} b)$
[Khodjamirian (2001)]

$$r_E^{(\pi\pi)} = \left[\left(1.8^{+0.5}_{-0.7}\right)\times 10^{-2}\right]_{\rm soft} + \left[\left(1.3^{+5.6}_{-5.2}\right) + i\left(-4.7^{+1.1}_{-0.3}\right)\right]_{\rm hard^{QCDF}} \times 10^{-2}$$

$$r_E^{(\pi\pi,6)} = \left[(-2.7 \pm 0.4)\times 10^{-2}\right]_{\rm hard^{QCDF}}$$

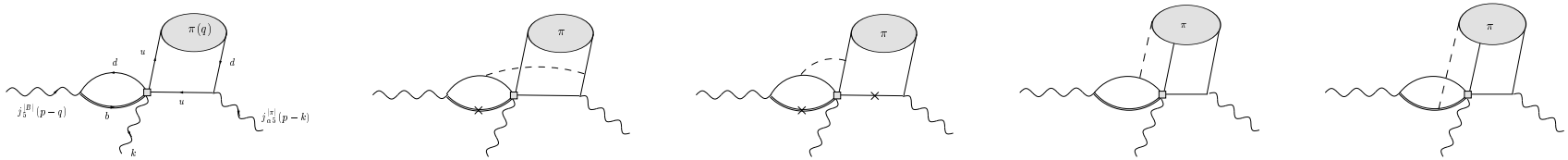
▷ PENGUIN CONTRIBUTIONS: [Khodjamirian, Mannel, BM (2003), Khodjamirian, Mannel, Urban (2002)]



$$r_{P_q}^{(\pi\pi)} = \left[0.11^{+0.02}_{-0.36} + i\left(1.1^{+0.2}_{-0.1}\right)\right]\times 10^{-2} \qquad r_{P_c}^{(\pi\pi)} = \left[-0.18^{+0.06}_{-0.68} + i\left(-0.80^{+0.17}_{-0.08}\right)\right]\times 10^{-2}$$

$$r_{P_b}^{(\pi\pi)} = \left(0.93^{+0.09}_{-0.65}\right)\times 10^{-2} \qquad r_{8g}^{(\pi\pi)} = -\left(3.8^{+1.3}_{-0.4}\right)\times 10^{-2}$$

▷ ANNIHILATION: [Khodjamirian, Mannel, Melcher, BM (2005)]



$$r_A^{(\pi\pi)} = \left[-0.67^{+0.47}_{-0.87} + i\left(3.6^{+0.5}_{-1.1}\right)\right]\times 10^{-3}, \qquad R_A^{(\pi\pi,6)} = -\frac{2 f_B F_\pi^S(m_B^2)}{m_b f_\pi f_{B\pi}^+(0)} = 0.23^{+0.05}_{-0.08}, \qquad r_A^{(\pi\pi,(5,6))} \simeq 0$$

decay	BR(10^{-6})	BR(10^{-6})$_{th}$	a_{CP}	$(a_{CP})_{th}$
$B^- \to \pi^0\pi^-$	$5.59^{+0.41}_{-0.40}$	**5.30** (6.0)	0.06 ± 0.05	**-0.0003** (-0.0002)
$\bar{B}^0 \to \pi^+\pi^-$	5.16 ± 0.22	**7.00** (8.9)	0.38 ± 0.06	-0.08 (-0.065)
$\bar{B}^0 \to \pi^0\pi^0$	1.55 ± 0.19	0.38 (0.3)	$0.43^{+0.25}_{-0.24}$	**0.43** (0.45)
$B^- \to \pi^0 K^-$	12.9 ± 0.6	**9.8** (11.1)	0.050 ± 0.025	**0.06** (0.07)
$\bar{B}^0 \to \pi^+ K^-$	19.4 ± 0.6	**14.6** (16.3)	$-0.098^{+0.012}_{-0.011}$	0.058 (0.045)
			-0.069 ± 0.016	
$B^- \to \pi^-\bar{K}^0$	23.1 ± 1.0	**16.7** (19.3)	0.009 ± 0.025	- **0.013** (0.009)
$\bar{B}^0 \to \pi^0\bar{K}^0$	9.5 ± 0.5	**6.23** (7.0)	-	- 0.038 (- 0.033)
$B^- \to K^0 K^-$	$1.36^{+0.29}_{-0.27}$	**1.46** (1.36)	$0.12^{+0.17}_{-0.18}$	**0.275** (0.167)
	$1.11^{+0.20}_{-0.19}$		0.017 ± 0.168	
$\bar{B}^0 \to K^0\bar{K}^0$	$0.96^{+0.21}_{-0.19}$	**1.37** (1.35)	$-0.58^{+0.62}_{-0.54}$	0.288 (0.167)
	$1.26^{0.20}_{0.19}$			
$\bar{B}^0 \to K^+ K^-$	$0.15^{+0.11}_{-0.10}$	0.001 (0.013)	-	**0** (0)
	0.23 ± 0.14			
$\bar{B}^0_s \to \pi^+\pi^-$	0.57 ± 0.25	0.0004 (0.024)	-	**0** (0)
$\bar{B}^0_s \to \pi^0\pi^0$	-	**0.0002** (0.012)	-	**0** (0)
$\bar{B}^0_s \to \pi^- K^+$	5.0 ± 1.1	9.19 (10.2)	0.39 ± 0.17	-0.081 (- 0.067)
			0.15 ± 0.19	
$\bar{B}^0_s \to \pi^0 K^0$	-	**0.48** (0.49)	-	**0.40** (0.42)
$\bar{B}^0_s \to K^0\bar{K}^0$	< 66	**20.5** (24.7)	-	**-0.013** (0.009)
$\bar{B}^0_s \to K^+ K^-$	26.5 ± 4.4	**19.1** (22.7)	-	**0.057** (0.040)

Table:
$20 - 30\%$ error in LCSR results has to be considered;
$(\ldots)$ = QCDF default results;
LCSR predictions are more or less in the ballpark of QCDF results

topological amplitudes ($PA_{\rm EW}$ and $PE_{\rm EW}$ neglected):

$T, C, E, A \sim \lambda_u = V_{ub}^* V_{ud}$

$P, P_{\rm EW}, PE\ldots \sim \lambda_u + \lambda_c$

- tree-dominated decays

$$\begin{aligned}
\sqrt{2}\,\mathcal{A}_{B^-\to\pi^-\pi^0} &= (T+C) + P_{\rm EW} + P_{\rm EW}^C \\
\mathcal{A}_{\bar{B}^0\to\pi^+\pi^-} &= (T+E) + P + \frac{2}{3}P_{\rm EW}^C + PE + 2PA \\
-\mathcal{A}_{\bar{B}^0\to\pi^0\pi^0} &= (C-E) - P + P_{\rm EW} + \frac{1}{3}P_{\rm EW}^C - PE - 2PA
\end{aligned}$$

- penguin-dominated decays

$$\begin{aligned}
\mathcal{A}_{B^-\to\pi^-\bar{K}^0} &= (A') + P' - \frac{1}{3}P'^{C}_{\rm EW} + PE' \\
\sqrt{2}\,\mathcal{A}_{B^-\to\pi^0 K^-} &= (T'+A') + P' + \frac{2}{3}P'^{C}_{\rm EW} + PE' + [(C'_K) + P'_{{\rm EW},K}], \\
\mathcal{A}_{\bar{B}^0\to\pi^+ K^-} &= (T') + P' + \frac{2}{3}P'^{C}_{\rm EW} + PE' \\
\sqrt{2}\,\mathcal{A}_{\bar{B}^0\to\pi^0\bar{K}^0} &= -P' + \frac{1}{3}P'^{C}_{\rm EW} - PE' + [(C'_K)]
\end{aligned}$$

$$\begin{aligned}
\mathcal{A}_{B^-\to K^- K^0} &= (A) + P - \frac{1}{3}P_{\rm EW} + PE \\
\mathcal{A}_{\bar{B}^0\to\bar{K}^0 K^0} &= P - \frac{1}{3}P_{\rm EW} + PE + 2PA
\end{aligned}$$

- annihilation-dominated decay

$$\mathcal{A}_{\bar{B}^0\to K^- K^+} = (E) + 2PA$$

topological amplitudes - B_s decays ($PA_{\rm EW}$ and $PE_{\rm EW}$ neglected):

- tree-dominated decays

$$\begin{aligned}
\mathcal{A}_{\bar{B}_s\to\pi^-K^+} &= (T) + P + \frac{2}{3}P^C_{\rm EW} + PE \\
\sqrt{2}\,\mathcal{A}_{\bar{B}_s\to\pi^0K^0} &= (C) - P + P_{\rm EW} + \frac{1}{3}P^C_{\rm EW} - PE
\end{aligned}$$

- penguin-dominated decays

$$\begin{aligned}
\mathcal{A}_{\bar{B}_s\to\bar{K}^0K^0} &= P' - \frac{1}{3}P'^{\,C}_{\rm EW} + PE' + 2PA' \\
\mathcal{A}_{\bar{B}_s\to K^-K^+} &= (T'+E') + P' + \frac{2}{3}P'^{C}_{\rm EW} + PE' + 2PA'
\end{aligned}$$

- annihilation-dominated decay

$$\mathcal{A}_{\bar{B}_s\to\pi^+\pi^-} = (E') + 2PA'$$

$\Delta S = 0$ decays	$B \to \pi\pi$	$B \to K\,K$	$B_s \to \pi\,K$
$T\ (10^{-8})$	2.7075	0	3.20398
$C\,(10^{-8})$	0.656344	0	0.776699
$P\,(10^{-8})$	0.771186	1.29801	0.9126
$P_{EW}\ (10^{-8})$	0.0867236	0.145967	0.102626
$P_{EW}^{C}\ (10^{-8})$	0.0157459	0	0.0186332
$E\,(10^{-8})$	0.0223089	0.0375487	0
$A\,(10^{-8})$	0	0.00911183	0
$PE\,(10^{-8})$	0.0862121	0.145106	0.102021
$PA\,(10^{-8})$	0.0023204	0.00390552	0
$PE_{EW}\ (10^{-8})$	0.00165358	0.00278319	0.0019568
$PA_{EW}\ (10^{-8})$	0.000154581	0.000260179	0

$\Delta S = 1$ decays	$B_s \to \pi\pi$	$B_s \to K\,K$	$B \to \pi\,K$
$T'\ (10^{-8})$	0	0.913179	0.771675
$C'_K\ (10^{-8})$	0	0	0.20966
$P'\ (10^{-8})$	0	4.45482	3.76451
$P'_{EW}\ (10^{-8})$	0	0	0.558254
$P'^{C}_{EW}\ (10^{-8})$	0	0.103871	0.0877751
$E'\ (10^{-8})$	0.00518854	0.00752429	0
$A'\ (10^{-8})$	0	0	0.00154296
$PE'\ (10^{-8})$	0	0.585956	0.495158
$PA'\ (10^{-8})$	0.0108752	0.015771	0
$PE'_{EW,K}\ (10^{-8})$	0	0.0112388	0.00949731
$PA'_{EW}\ (10^{-8})$	0.000724489	0.00105064	0

PUZZLES in $B \to \pi\pi, \pi K, KK$ decays

- predicted BRs for penguin-dominated $B \to PP$ decays are systematically somewhat lower than the measurements
- color-suppressed tree-dominated $B \to \pi^0\pi^0$ BR is predicted too low
- direct CP asymmetries $a_{\rm CP}(\overline{B}^0 \to \pi^+ K^-)$, $a_{\rm CP}(\overline{B}^0 \to \pi^+\pi^-)$ and $a_{\rm CP}(\overline{B}_s \to \pi^- K^+)$ disagree with the data in the sign
- $\Delta a_{\rm CP}(B \to \pi K) = a_{\rm CP}(B \to \pi^0 K^-) - a_{\rm CP}(B \to \pi^+ K^-) = 0.121 \pm 0.022$ by including the most recent Belle results; expected $\Delta a_{\rm CP}(B \to \pi K) = 0$
- annihilation-dominated decays $B \to K^+K^-$ and $B_s \to \pi^+\pi^-$ cannot be explained, unless by introducing ad hoc large annihilation contribution with a large phase

▷ SOLUTIONS ?

▷ large C/T-amplitude with a large phase $\to$ for $a_{\rm CP}$ and BR of $\pi^0\pi^0$ puzzle
▷ large $P_{\rm EW}$-amplitude with a large phase $\to$ for $B \to K\pi$ puzzle
▷ large PE-amplitude with a large phase $\to$ for puzzles in $\Delta S = 1$ modes but not for $\pi^0\pi^0$ problems
▷ large FSI - D, D^* exchange $\to$ for color-suppressed neutral modes $\pi^0\pi^0$, $\pi^0 K^0$

▷ SOLUTIONS for $B_{(s)} \to PP(P = \pi, K)$ puzzles with the LCSR input ?

[M. Jung, A. Khodjamirian, BM, in preparation]

Preliminary!

- ▷ we plan to use CKMfitter with the LCSR input (decay constants, form factors, different contributions and topologies) to perform the fit to $B_{(s)} \to PP(P = \pi, K)$ decays
- ▷ we use different scenarios, trying to minimize the input, and to obtain all BRs and CP asymmetries simultaneously
- ▷ isospin decomposition of amplitudes - a relative phase is introduced which is varied in a full range
- ▷ annihilation topologies - extracted from the measured annihilation dominated decays
- ▷ predictions for B_s decays

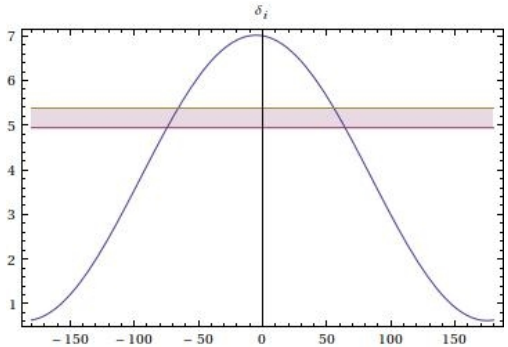
ISOSPIN PHASE

▷ general isospin decomposition - $B \to \pi\pi$ amplitudes:

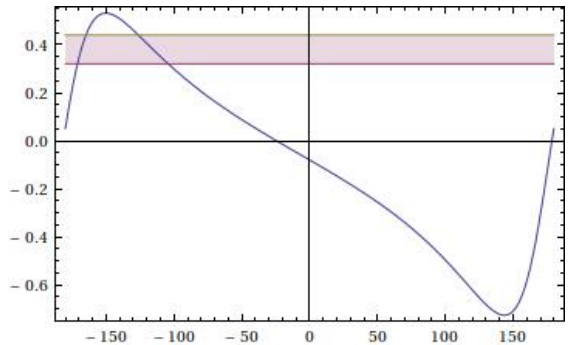
$$
\begin{aligned}
A(B^- \to \pi^-\pi^0) &= \langle \pi^-\pi^0 | H_{\rm eff} | B^- \rangle &&= \frac{3}{\sqrt{2}} A_2 \,, \\
A(\bar{B}^0 \to \pi^+\pi^-) &= \langle \pi^+\pi^- | H_{\rm eff} | \bar{B}^0 \rangle &&= A_2 + A_0 e^{\delta_I} \,, \\
A(\bar{B}^0 \to \pi^0\pi^0) &= \langle \pi^0\pi^0 | H_{\rm eff} | \bar{B}^0 \rangle &&= 2A_2 - A_0 e^{\delta_I} \,,
\end{aligned}
$$

$$
\begin{aligned}
A_2 &= \frac{1}{3}\left((T+C) + P_{\rm EW} + P^C_{\rm EW}\right) \\
A_0 &= \frac{1}{3}\left((2T - C + 3E) + 3P - P_{\rm EW} + P^C_{\rm EW} + 3PE + 6PA - PE_{\rm EW} + PA_{\rm EW}\right)
\end{aligned}
$$

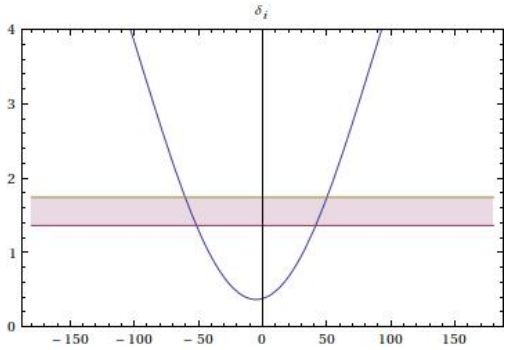
$\Rightarrow$ in A_0 amplitude we miss a proper treatment of nonemission topologies (penguin and/or annihilation diagrams) and final state effects $\to$ we introduce a relative phase between the isospin amplitudes, δ_I:



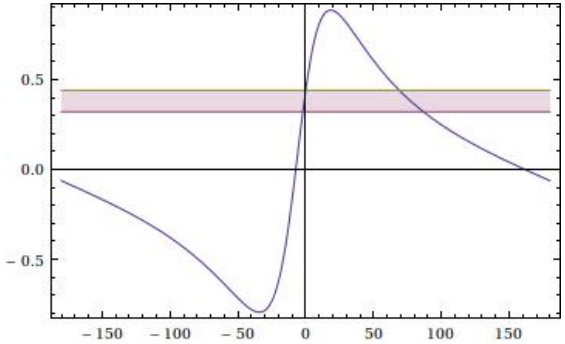
$BR(B \to \pi^+\pi^-)$



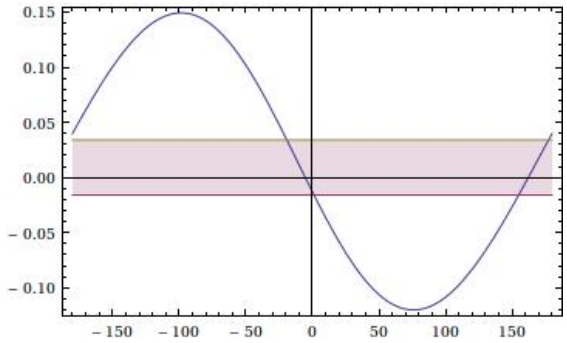
$a_{\rm CP}(B \to \pi^+\pi^-)$



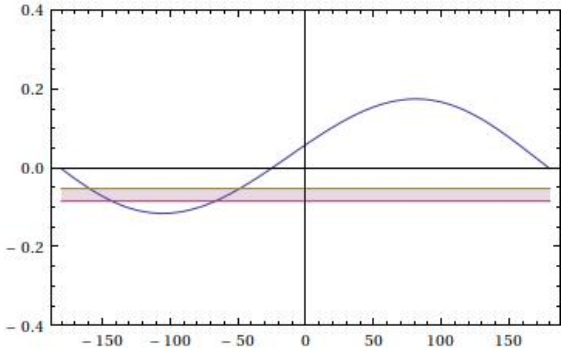
$BR(B \to \pi^0\pi^0)$



$a_{\rm CP}(B \to \pi^0\pi^0)$

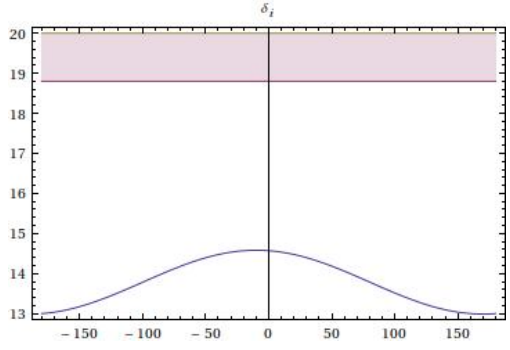


$a_{\rm CP}(B \to \pi^0 K^-)$



$a_{\rm CP}(B \to \pi^+ K^-)$

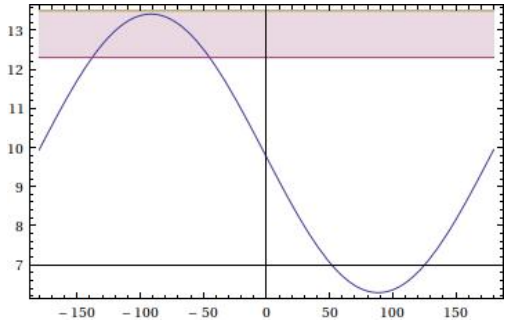
- unfortunatelly, this does not solve the "$B \to \pi K$" puzzle, since asymmetries flip the sign simultaneously



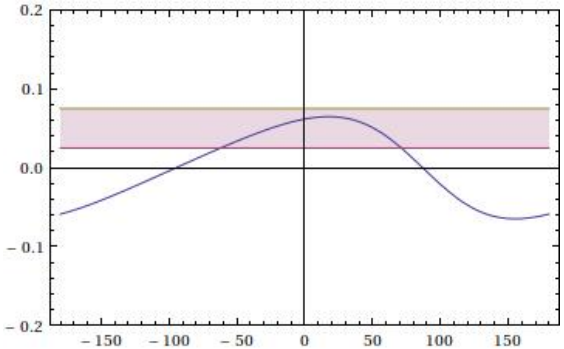
$BR's(B \to \pi K)$ still a bit too low

PENGUIN PHASE

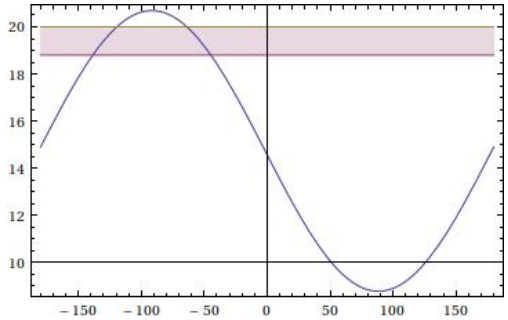
▷ unique nonperturbative phase is added to the penguin amplitudes calculated in LCSRs (r_P, r_{8g}, $r_{7\gamma}$) - P, $P^{\rm C}_{\rm EW}$:
- it does not solve the problems in $B \to \pi\pi$ decays (tree-dominated)
- influence on the penguin-dominated $B \to \pi K$ decays:



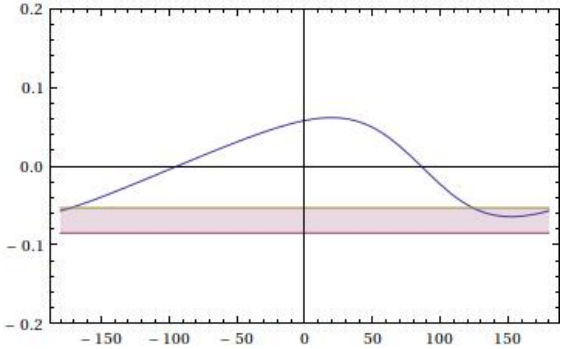
$BR(B \to \pi^0 K^-)$



$a_{\rm CP}(B \to \pi^0 K^-)$

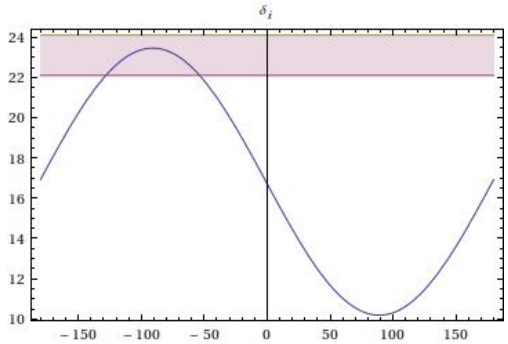


$BR(B \to \pi^+ K^-)$

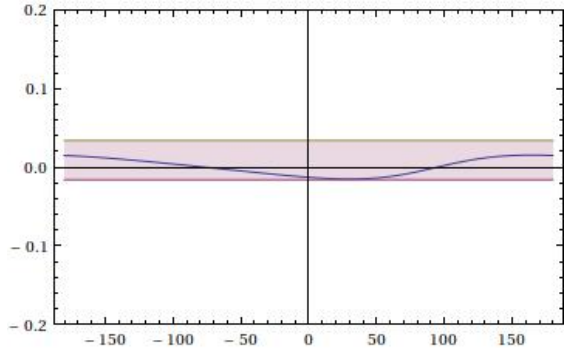


$a_{\rm CP}(B \to \pi^+ K^-)$

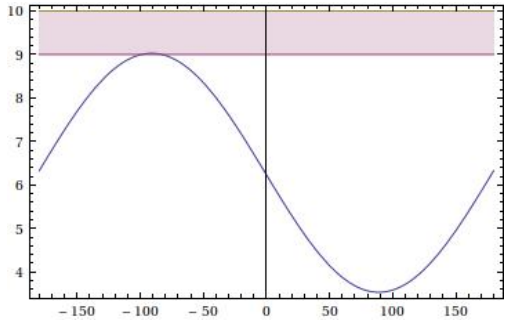
again the same situation, adjusting $a_{\rm CP}(B \to \pi^+ K^-)$ spoils $a_{\rm CP}(B \to \pi^0 K^-)$ prediction



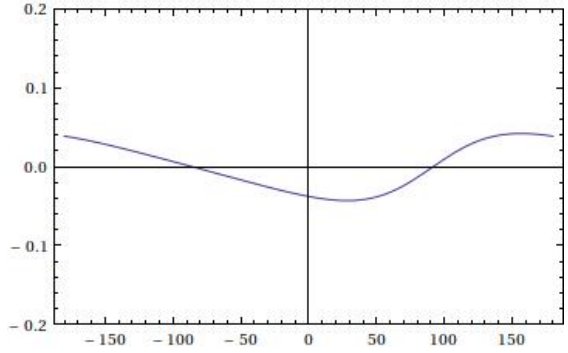
$BR(B \to \pi^- K^0)$



$a_{\mathrm{CP}}(B \to \pi^- K^0)$



$BR(B \to \pi^0 K^0)$



$a_{\mathrm{CP}}(B \to \pi^0 K^0)$

ANNIHILATION PHASE

▷ pengin-annihilation part PA is fitted to the data using recently measured penguin-dominated decays $B \to K^+K^-$ and $B_s \to \pi^+\pi^-$

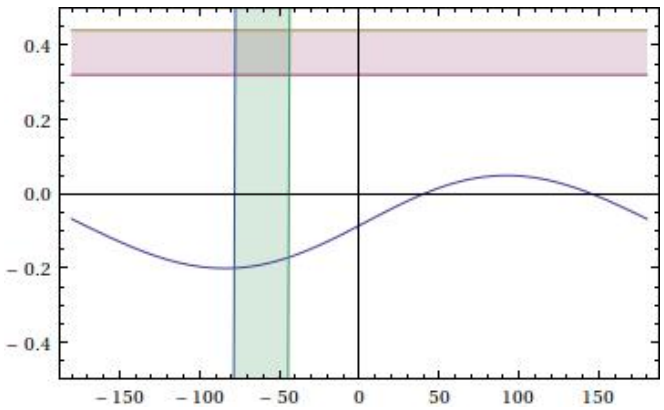
fitted values:

$\Delta S = 0$ decays	B $\to \pi\pi$	B $\to$ K K
PA (10^{-8})	0.0023204	0.00390552
PA(fit) (10^{-8})	0.09 ± 0.02	0.15 ± 0.03

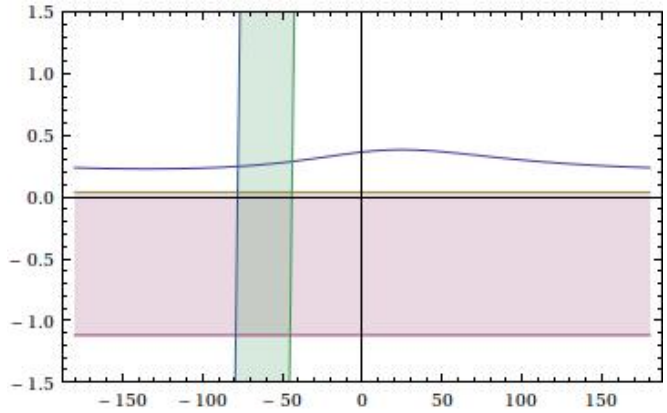
$\Delta S = 1$ decays	$B_s \to \pi\pi$	$B_s \to$ K K
PA' (10^{-8})	0.0108752	0.015771
PA'(fit) (10^{-8})	0.43 ± 0.09	0.62 ± 0.13

predictions:

decay	BR(10^{-6})	BR$(10^{-6})_{th}$	a_{CP}	$(a_{CP})_{th}$
$\bar{B}^0 \to \pi^+\pi^-$	5.16 ± 0.22	(7.00) 6.8 ± 0.1	0.38 ± 0.06	(-0.08) fig
$\bar{B}^0 \to \pi^0\pi^0$	1.55 ± 0.19	(0.38) 0.29 ± 0.05	$0.43^{+0.25}_{-0.24}$	(0.43) [0.26,0.66]
$\bar{B}^0 \to K^0\bar{K}^0$	$0.96^{+0.21}_{-0.19}$ $1.26^{0.20}_{0.19}$	(1.37) 1.2 ± 0.2	$-0.58^{+0.62}_{-0.54}$	(0.288) fig
$\bar{B}^0 \to K^+K^-$	$0.15^{+0.11}_{-0.10}$ 0.23 ± 0.14	(0.001) 0.08 ± 0.03	-	(0) [-0.23,0.23]
$\bar{B}^0_s \to \pi^+\pi^-$	0.57 ± 0.25	(0.0004) 0.63 ± 0.24	-	(0) [-0.01,0.01]
$\bar{B}^0_s \to K^0\bar{K}^0$	< 66	(20.5) [13.7, 29.0]	-	(-0.013) [-0.15,0.10]
$\bar{B}^0_s \to K^+K^-$	26.5 ± 4.4	(19.1) [12.5,27.2]	-	(0.057) [-0.10,0.17]



$a_{\mathrm{CP}}(B \to \pi^+\pi^-)$



$a_{\mathrm{CP}}(B \to K^0K^0)$

CKMfitter is needed for a more reliable fit

CONCLUSIONS

- LCSRs are providing the input for the factorizable contributions - form factors and decay constants
- within LCSRs the predictions for penguins and the annihilation part (finite!) are given
- predictions for BR's are in the ballpark of QCDF results
- with the LCSRs $1/m_b$ -effects are calculable
- the puzzles remain!
- adding arbitrary phases to isospin and penguin parts does not bring an agreement with the data
- more elaborated fits will be done by using CKMfitter [M. Jung, A. Khodjamirian, B.M., in preparation]
- pessimistic view:
  hadronic final-state interactions are probably more important that we have first thought - inelastic intermediate states can mix up different toplogies; effects are not accessible with QCD techniques

- $B \to PP$ decays, with the current set of data remain a challenge!