$B \to \pi K$ Puzzle and New Physics

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Based on

- SB, C-W. Chiang, D. London, PLB675 (2009)
- SB, C-W. Chiang, M. Gronau, D. London, J. L. Rosner, PLB678 (2009)

Outline

1. The $B \to \pi K$ decays as a test of CKM framework
2. The SM fitting
3. The NP fitting
4. Sum rules and $A_{CP}(\pi^0 K^0)$
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The $B \to \pi K$ decays as a test of CKM framework

- Four $B \to \pi K$ decays, related by isospin

$$A(B^0 \to \pi^- K^+) - \sqrt{2}A(B^+ \to \pi^0 K^+) + \sqrt{2}A(B^0 \to \pi^0 K^0) - A(B^+ \to \pi^+ K^0) = 0$$

- In terms of diagrams, Penguin (P'_{tc} and P'_{uc}), tree(T'), color-suppressed tree (C'), annihilation (A'), color-favored (suppressed) EW penguin ($P'^{(C)}_{EW}$),

$$\begin{aligned}
A^{+0} &= -P'_{tc} + P'_{uc}e^{i\gamma} + A'e^{i\gamma} - \frac{1}{3}P'^{C}_{EW} \ , \\
\sqrt{2}A^{0+} &= +P'_{tc} - P'_{uc}e^{i\gamma} - T'e^{i\gamma} - C'e^{i\gamma} - A'e^{i\gamma} - P'_{EW} - \frac{2}{3}P'^{C}_{EW} \ , \\
A^{-+} &= +P'_{tc} - P'_{uc}e^{i\gamma} - T'e^{i\gamma} - \frac{2}{3}P'^{C}_{EW} \ , \\
\sqrt{2}A^{00} &= -P'_{tc} + P'_{uc}e^{i\gamma} - C'e^{i\gamma} - P'_{EW} - \frac{1}{3}P'^{C}_{EW} \ . \qquad (1)
\end{aligned}$$

The $B \to \pi K$ decays as a test of CKM framework

- Or more compactly,

$$
\begin{aligned}
A^{+0} &= p' \ , \\
\sqrt{2}A^{0+} &= -p' - t' - c' \ , \\
A^{-+} &= -p' - t' \ , \\
\sqrt{2}A^{00} &= p' - c' \ ,
\end{aligned} \tag{2}
$$

where

$$
\begin{aligned}
p' &= -P'_{tc} + P'_{uc} e^{i\gamma} - \frac{1}{3} P'^{C}_{EW} \ , \\
t' &= T' e^{i\gamma} + P'^{C}_{EW} \ , \\
c' &= C' e^{i\gamma} + P'_{EW} .
\end{aligned} \tag{3}
$$

- We can see $(T' e^{i\gamma}, P'^{C}_{EW})$ and $(C' e^{i\gamma}, P'_{EW})$ appear together.

The $B \to \pi K$ decays as a test of CKM framework

- Using flavor SU(3), we can relate the EWP to the trees: Neubert, Rosner(1998), Gronau, Pirjol, Yuan (1999)

$$\begin{aligned} P'_{EW} &\approx -0.60\,T' \\ P'^{C}_{EW} &\approx -0.60\,C'. \end{aligned}$$

- Hierarchy between the diagrams: Gronau, Hernandez, London, Rosner(1994,1995)

$$\begin{array}{ccc} 1 & : & P'_{tc} \\ \mathscr{O}(\overline{\lambda}) & : & |T'|, P'_{EW} \\ \mathscr{O}(\overline{\lambda}^2) & : & |C'|, P'_{uc}, P'^{C}_{EW} \\ \mathscr{O}(\overline{\lambda}^3) & : & |A'| \end{array}$$

$\overline{\lambda} = 0.2 - 0.3$

The experimental data as of 2009 (2007)

Mode	$\mathscr{B}(10^{-6})$	A_{CP}	S_{CP}
$B^+ \to \pi^+ K^0$	23.1 ± 1.0	0.009 ± 0.025	
	(23.1 ± 1.0)	(0.009 ± 0.025)	
$B^+ \to \pi^0 K^+$	12.9 ± 0.6	0.050 ± 0.025	
	(12.8 ± 0.6)	(0.047 ± 0.026)	
$B^0 \to \pi^- K^+$	19.4 ± 0.6	$-0.098^{+0.012}_{-0.011}$	
	(19.7 ± 0.6)	(-0.093 ± 0.015)	
$B^0 \to \pi^0 K^0$	9.8 ± 0.6	-0.01 ± 0.10	0.57 ± 0.17
	(10.0 ± 0.6)	(-0.12 ± 0.11)	(0.33 ± 0.21)

$A_{CP}(\pi^- K^+)$ vs $A_{CP}(\pi^0 K^+)$

- If $|C'| \ll |T'|$, $A_{CP}(\pi^- K^+) \approx A_{CP}(\pi^0 K^+)$.
- However, the data show,

  $A_{CP}(\pi^0 K^+) - A_{CP}(\pi^- K^+) = 0.148 \pm 0.028 (5.3\sigma)$.

  NP? Belle collaboration, Nature (2008); M. Peskin, Nature (2008)
- $|C'/T'| = 0.58$ and large negative $\arg(C'/T')$ can account for the difference.
- $|C'/T'| = 0.58$ is okay with QCD calculations.

  Bauer, Pirjol, Rothstein, Stewart, PRD(2004); Bauer, Rothstein, Stewart, PRL(2005)

  Beneke and Jager, NPB(2006)

  Li and Mishima, arXiv:0901
- large negative $\arg(C'/T')$ is accounted for only in Li and Mishima, arXiv:0901

The SM Fit 1

$\chi^2_{min}/d.o.f.(c.l.)$	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$	$\lvert P'_{uc}\rvert$
$0.52/1(47\%)$	67.7 ± 11.8	19.6 ± 6.9	14.9 ± 6.6	20.5 ± 13.3
$\delta_{T'}$	$\delta_{C'}$	$\delta_{P'_{uc}}$	β	γ
$(6.0 \pm 4.0)^\circ$	$(-11.7 \pm 6.8)^\circ$	$(-0.7 \pm 2.3)^\circ$	$(21.66 \pm 0.95)^\circ$	$(35.3 \pm 7.1)^\circ$

Table: Results of the fit to P'_{tc}, T', C', P'_{uc}, β and γ in the SM. The fit includes the constraint $\beta = (21.66^{+0.95}_{-0.87})^\circ$. The amplitude is in units of eV.

- Better fit than to 2007 data (SB and D. London, PLB(2007)) where $|C'/T'| = 1.6 \pm 0.3$.
- Still γ too small. cf) CKM fit $\gamma = (66.8^{+5.4}_{-3.8})^\circ$.
- $|P'_{uc}|$ is large so is its error.

The SM Fit 2

$\chi^2_{min}/d.o.f.$	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$	$\lvert P'_{uc}\rvert$
$3.2/2(20\%)$	50.5 ± 1.8	5.9 ± 1.8	3.4 ± 1.0	2.3 ± 4.9
$\delta_{T'}$	$\delta_{C'}$	$\delta_{P'_{uc}}$	β	γ
$(25.5 \pm 11.2)^\circ$	$(252.0 \pm 36.1)^\circ$	$(-9.9 \pm 27.8)^\circ$	$(21.65 \pm 0.95)^\circ$	$(66.5 \pm 5.5)^\circ$

Table: Results of the fit to P'_{tc}, T', C', P'_{uc}, β and γ in the SM. The fit includes the constraints $\beta = (21.66^{+0.95}_{-0.87})^\circ$ and $\gamma = (66.8^{+5.4}_{-3.8})^\circ$. The amplitude is in units of eV.

- The quality of fit becomes poorer than (I).
- $|T'/P'_{tc}|$ small.

Predictions of the $B \to \pi K$ observables

Obs.	Fit 1	Fit 2
$BR(\pi^+ K^0)$	$23.1\ (+0.02)$	$23.7\ (-0.57)$
$A_{CP}(\pi^+ K^0)$	$0.014\ (-0.21)$	$0.016\ (-0.29)$
$BR(\pi^0 K^+)$	$12.9\ (-0.03)$	$12.5\ (+0.72)$
$A_{CP}(\pi^0 K^+)$	$0.05\ (+0.15)$	$0.04\ (+0.27)$
$BR(\pi^- K^+)$	$19.4\ (+0.05)$	$19.7\ (-0.46)$
$A_{CP}(\pi^- K^+)$	$-0.098\ (-0.04)$	$-0.097\ (-0.12)$
$BR(\pi^0 K^0)$	$9.8\ (-0.07)$	$9.3\ (+0.88)$
$A_{CP}(\pi^0 K^0)$	$-0.08\ (+0.66)$	$-0.12\ (+1.10)$
$S_{CP}(\pi^0 K^0)$	$0.58\ (-0.03)$	$0.58\ (-0.08)$

Table: Predictions of the $B \to \pi K$ decay observables. Numbers in parentheses are the corresponding pulls. pull $\equiv$ (data-theory prediction)/(data error)

Predictions of the $B \to \pi K$ observables

- The prediction $A_{CP}(\pi^0 K^0) = -0.12$ has the largest deviation from the data.
- BaBar and Belle data are inconsistent in the central values of $A_{CP}(\pi^0 K^0)$.

Source	$N(B\bar{B})$ (M)	$A_{CP}(\pi^0 K^0)$
BaBar	467	$-0.13 \pm 0.13 \pm 0.03$
Belle	657	$0.14 \pm 0.13 \pm 0.06$
Average	1124	-0.01 ± 0.10

- The SM favors the BaBar data.

NP contributions

- $p' \to p' + P'_{\rm NP} e^{i\Phi'_P}$ (NP Fit 1)
- $c' \to c' + P'_{\rm EW,NP} e^{i\Phi'_{\rm EW}}$ (NP Fit 2)
- $t' \to t' + P'^C_{\rm EW,NP} e^{i\Phi'^C_{\rm EW}}$ (NP Fit 3)
- NP strong phase is small, $\delta_{\rm NP} = \delta_{T'}$ A. Datta and D. London, PLB(2004)
- For NP fits, we impose $\beta = (21.66^{+0.95}_{-0.87})^\circ$ and $\gamma = (66.8^{+5.4}_{-3.8})^\circ$

NP 1 $\chi^2/d.o.f.$	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$
$3.6/2(17\%)$	NA	5.9 ± 2.0	3.6 ± 1.0
$\lvert P'_{NP}\rvert$	$\delta_{C'}$	δ_{NP}	Φ'_P
NA	NA	NA	NA

NP 2 $\chi^2/d.o.f.$	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$
$0.4/2(82\%)$	48.2 ± 1.3	2.6 ± 0.4	16.1 ± 28.4
$\lvert P'_{EW,NP}\rvert$	$\delta_{C'}$	δ_{NP}	Φ'_{EW}
20.1 ± 22.3	$(254.8 \pm 21.8)^\circ$	$(95.4 \pm 9.6)^\circ$	$(37.6 \pm 51.8)^\circ$

NP 3 $\chi^2/d.o.f.$	$\lvert P'_{tc}\rvert$	$\lvert T'\rvert$	$\lvert C'\rvert$
$2.5/2(28\%)$	48.2 ± 1.3	1.9 ± 1.4	9.4 ± 2.3
$\lvert P'^C_{EW,NP}\rvert$	$\delta_{C'}$	δ_{NP}	Φ'^C_{EW}
16.5 ± 15.2	$(192.4 \pm 12.3)^\circ$	$(97.8 \pm 15.3)^\circ$	$(183.9 \pm 7.8)^\circ$

Predicts too large C' in the 2nd and 3rd case.

Predictions of $A_{CP}(\pi^0 K^0)$

SM 2	NP 1 (P)	NP 2 (EW)	NP 3 (EWC)	NP (2+3)
-0.12	-0.12	$+0.10$	-0.03	-0.03

- The predictions of $A_{CP}(\pi^0 K^0)$ are very distictive depending on models.
- Therefore, $A_{CP}(\pi^0 K^0)$ can be used to distinguish different models, if theoretical and experimental errors are controllable. SB, C-W. Chiang, M. Gronau, D. London, J. L. Rosner, arXiv:0905.1495

Sum rules and $A_{CP}(\pi^0 K^0)$

- In the SM, $A_{CP}(\pi^0 K^0)$ can be predicted quite reliably.
- The dominant $\Delta I = 0$ term (p') is canceled in

$$\begin{aligned} & 2|A^{0+}|^2 + 2|A^{00}|^2 - |A^{+0}|^2 - |A^{-+}|^2 \\ = \; & |p' + t' + c'|^2 + |p' - c'|^2 - |p' + t'|^2 - |p'|^2 \\ = \; & 2(|c'|^2 + \mathrm{Re}(t' c'^*)) \end{aligned}$$

The RHS is small compared with the dominant $|p'|^2$ in the SM.

Sum rules and $A_{CP}(\pi^0 K^0)$

- Sum rule for the branching ratios M. Gronau and J. L. Rosner, PRD(1999), H. J. Lipkin, PLB(1999)

$$2\mathscr{B}(\pi^0 K^+) + 2(\tau_+/\tau_0)\mathscr{B}(\pi^0 K^0) = (\tau_+/\tau_0)\mathscr{B}(\pi^- K^+) + \mathscr{B}(\pi^+ K^0) \ .$$

  where $\tau_+/\tau_0 = 1.073 \pm 0.008$

- Numerically

$$46.8 \pm 1.8 = 43.9 \pm 1.2\,(1.3\sigma)$$

- The $\mathscr{B}$ has been measured precisely and all the SM and NP fits confirm the rate sum rule.

Sum rules and $A_{CP}(\pi^0 K^0)$

- Sum rule for the A_{CP} M. Gronau, PLB(2005)

$$A_{CP}(\pi^- K^+) + A_{CP}(\pi^+ K^0) \simeq A_{CP}(\pi^0 K^+) + A_{CP}(\pi^0 K^0) \ .$$

  where $\mathscr{B}(\pi^0 K^+) : \mathscr{B}(\pi^0 K^0) : \mathscr{B}(\pi^- K^+) : \mathscr{B}(\pi^+ K^0) = 1 : 1 : 2 : 2$ is assumed.

- Prediction $A_{CP}(\pi^0 K^0) = -0.139 \pm 0.037$
- Taking into account of the correct values of $\mathscr{B}$, $A_{CP}(\pi^0 K^0) = -0.149 \pm 0.044$
- These sum rule predictions of $A_{CP}(\pi^0 K^0)$ are consistent with the values obtained in the SM fits: $A_{CP}(\pi^0 K^0) = -0.08$ (SM Fit 1) -0.12 (SM Fit 2)

Sum rules and $A_{CP}(\pi^0 K^0)$

- Sum rules can be significantly violated with the presense of sizable $\Delta I = 1$ NP amplitude.
- With $P_1 \equiv P_{EW,NP}$ and $P_2 \equiv P^C_{EW,NP}$, the terms violating the rate sum rule are

$$2[|P_1|^2 + |P_1||P_2|\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)] \ ,$$

  where δ_1, δ_2 and ϕ_1, ϕ_2 are the strong and weak phases of P_1 and P_2.
- The term violating the asymmetry sum rule is

$$2|P_1||P_2|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2) \ ,$$

  which is violated significantly only when $P_1 \neq 0$, $P_2 \neq 0$, $\delta_1 \neq \delta_2$ and $\phi_1 \neq \phi_2$

Sum rules and $A_{CP}(\pi^0 K^0)$

Model	$A_{CP}(\pi^0 K^0)$	LHS of rate SR	RHS of rate SR
SM 2	-0.12	44.8	44.8
NP 1	-0.12	44.9	44.8
NP 2	$+0.10$	46.9	43.9
NP 3	-0.03	45.3	44.6
NP (2+3)	-0.03	47.0	43.8

- NP models can violate the asymmetry sum rule significantly while preserving the rate sum rule.

Conclusions

- While the $B \to \pi K$ puzzle has not disappeared, it has become weaker.
- The SM predicts $A_{CP}(\pi^0 K^0) = -0.149 \pm 0.044$, whose world average is -0.01 ± 0.10.
- More precise measurement of $A_{CP}(\pi^0 K^0)$ will allow the probe of NP in $\Delta I = 1$ transition amplitude.