$B \to \pi\pi, \pi K$ Puzzles and Hints for New Physics

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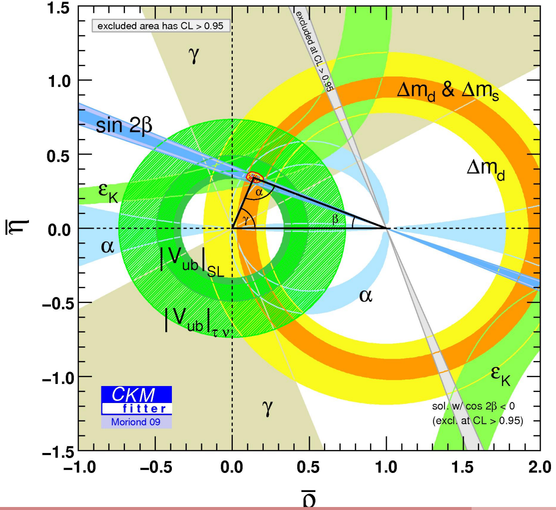
Outline

Introduction

B-physics at B-factories and Tevatron

- B-physics programs at current colliders have been very successful.



B-physics at the LHC era

- LHCb is a dedicated detector for B-physics.
- So B-physics will continue to be exciting at the LHC era. And it is complementary to the direct NP searches at ATLAS and CMS.
- Rare decays like $B_s \to J/\psi\phi$, $B_s \to \phi\phi$, $B_s \to \mu^+\mu^-$, $B_s \to K^*\mu^+\mu^-$, $B_s \to K^+K^-$ will be measured with unprecidented precisions and will confirm NP or rule out many NP models.
- Precision measurements of the SM parameters, eg, the inner angles of the unitarity triangle.

CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

To all orders in λ,

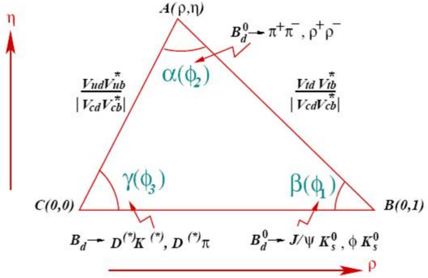
$$s_{12} = \lambda\,, \qquad s_{23} = A\lambda^2\,, \qquad s_{13}e^{-i\delta} = A\lambda^3(\varrho - i\eta)$$

$$\hat{V} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Unitarity Triangle

Unitarity of V_{CKM}

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Time dependent CP-asymmetries

- The time-dependent CP asymmetry:

$$A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = S_{CP} \sin \Delta m \Delta t + A_{CP} \cos \Delta m \Delta t$$

-

$$A_{CP} = -C_{CP} = \frac{1 - |\lambda_{CP}|^2}{1 + |\lambda_{CP}|^2}, \quad S_{CP} = -\frac{2\,\mathrm{Im}\lambda_{\mathrm{CP}}}{1 + |\lambda_{CP}|^2}, \quad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

$B \to \pi\pi$ and $B \to \pi K$ puzzles

Nonleptonic decays $B \to \pi\pi$ and $B \to \pi K$

- At quark level, $\bar{b} \to \bar{d}(\bar{s})q\bar{q}, \quad (q = u, d)$
- Effective theory at $m_b \ll M_W$,

$$H_{eff} = \sum_i c_i(\mu) O_i(\mu)$$

- Theories for

$$\langle M_1 M_2 | O_i(\mu) | B \rangle$$

: naive factorization, generalized factorization, QCDF, PQCD, SCET, ...

- $\Rightarrow$ No standard theory, yet...

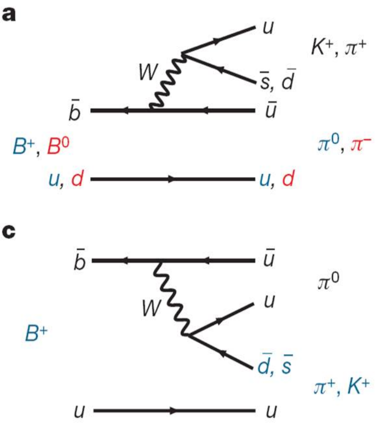
The $B \to \pi K$ decays as a test of CKM framework

- 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 ($P'^{(C)}_{EW}$),

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



Gronau, Hernandez, London, Rosner(1994,1995)

The $B \to \pi K$

- 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

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

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

$B \to \pi\pi$

- $$\begin{aligned} \sqrt{2}A(B^+ \to \pi^+\pi^0) &= -\left(\widetilde{T}e^{i\gamma} + \widetilde{C}e^{i\gamma}\right) \\ A(B^0 \to \pi^+\pi^-) &= -\left(\widetilde{T}e^{i\gamma} + P_{tc}e^{-i\beta}\right) \\ \sqrt{2}A(B^0 \to \pi^0\pi^0) &= P_{tc}e^{-i\beta} - \widetilde{C}e^{i\gamma} \end{aligned}$$

  where $\widetilde{T} = T + P_{uc}, \quad \widetilde{C} = C - P_{uc}$

- Isospin relation:

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

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

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

- The SU(3) breaking is estimated to be less than 5 % Neubert, Rosner(1998)

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

- Hierarchy between the diagrams: $(B \to \pi K)$ Gronau, Hernandez, London, Rosner(1994,1995)

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

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

- $(B \to \pi\pi)$

$$
\begin{array}{ccc}
1 & : & |T| \\
\mathcal{O}(\bar{\lambda}) & : & |C|, |P| \\
\mathcal{O}(\bar{\lambda}^2) & : & P_{EW} \\
\mathcal{O}(\bar{\lambda}^3) & : & P^{C}_{EW}
\end{array}
$$

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)

The experimental data as of 2008

	$BR[10^{-6}]$	A_{CP}	S_{CP}
$\pi^+\pi^0$	5.7±0.4	0.04±0.05	
$\pi^+\pi^-$	5.16±0.22	0.38±0.07	-0.61±0.08
$\pi^0\pi^0$	1.31±0.21	0.36±0.33	
π^+K^0	23.1±1.0	0.009±0.025	
π^0K^+	12.9±0.6	0.050±0.025	Belle, Nature(2008)
π^-K^+	19.4±0.6	-0.097±0.012	
π^0K^0	9.9±0.6	-0.14±0.11	0.38±0.19

$B \to \pi\pi, B \to \pi K$ puzzles

- In the SM, we expect

$$
\begin{aligned}
B(B \to \pi^0\pi^0) &\approx \mathcal{O}(\lambda^2) \times B(B^+ \to \pi^+\pi^0) \\
A_{CP}(B^+ \to \pi^0 K^+) &\approx A_{CP}(B^0 \to \pi^- K^+) \\
S_{CP}(B^0 \to \pi^0 K^0) &\approx \sin 2\beta
\end{aligned}
$$

- However, experimental data violate these relations significantly!!
- $B \to \pi\pi$ puzzle, $B \to \pi K$ puzzle

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

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NEWS & VIEWS

PARTICLE PHYSICS

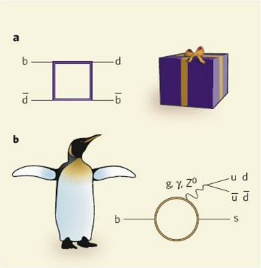
Song of the electroweak penguin

Michael E. Peskin

An unexpected imbalance in how particles containing the heaviest quarks decay might reveal exotic influences — and perhaps help to explain why matter, rather than antimatter, dominates the Universe.

Elsewhere in this issue, the Belle collaboration, based at the electron–positron particle collider of the high-energy accelerator laboratory KEK in Japan, announces their measurement of an anomalous asymmetry in the decay rates of exotic particles known as B mesons (Lin *et al.*, page 332)[1]. Combined with recent measurements of the same decays from the BaBar collaboration[2,3], a similar experiment at the Stanford Linear Accelerator Center (SLAC) in California, the new finding provides a tantalizing glimpse of a possible new source for a very fundamental asymmetry: the dominance of matter over antimatter in our Universe.

The two great principles of modern physics, quantum mechanics and Einstein's relativity,



time only three types of quark were known: up (u), down (d) and strange (s). But in the following decades, three more were discovered: charm (c), and the heavy bottom (b) and top (t) quarks. This astounding success led to the proposal[6,7] that specific experiments on B mesons — quark–antiquark pairings in which one of the particles is a b quark or $\bar{b}$ antiquark — could test the Kobayashi–Maskawa (KM) theory directly. The idea, proposed by Pier Oddone, that these experiments could be performed by colliding two beams of different energies, one of electrons and one of positrons (the antiparticle of the electron), motivated the construction of new accelerators at KEK and SLAC. In 2002, both BaBar[8] and Belle[9] reported

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

- $|C'/T'| = 0.58$ and large negative $\arg(C'/T')$ can account for the difference.

$$A_{CP}(0+) \approx -2\left|\frac{T'}{P'_{tc}}\right| \sin\delta_{T'} \sin\gamma,$$
$$A_{CP}(-+) \approx -2\left|\frac{T'}{P'_{tc}}\right| \sin\delta_{T'} \sin\gamma - 2\left|\frac{C'}{P'_{tc}}\right| \sin\delta_{C'} \sin\gamma$$

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

- $|C'/T'| = 0.58$ 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

Current status of $B \to \pi K$ puzzle and $A_{CP}(\pi^0 K^0)$

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

$\chi^2_{min}/d.o.f.$	$\vert P'_{tc}\vert$	$\vert T'\vert$	$\vert C'\vert$	$\vert P'_{uc}\vert$
$3.2/2(20\%)$	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
$(25.5\pm11.2)^\circ$	$(252.0\pm36.1)^\circ$	$(-9.9\pm27.8)^\circ$	$(21.65\pm0.95)^\circ$	$(66.5\pm5.5)^\circ$

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.

Best fit values 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

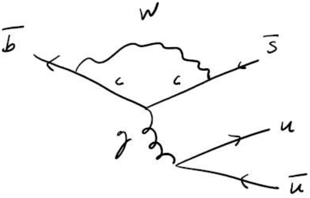
- The SM favors the BaBar data.

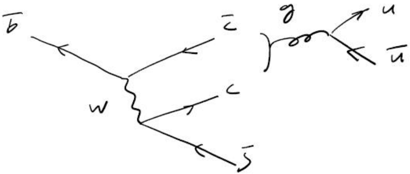
NP contributions

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

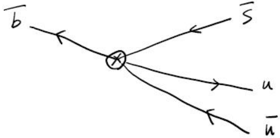
NP strong phase

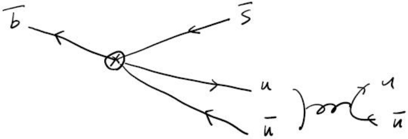
The strong phase, eg., of P'_c





NP strong phase comes only from self-rescattering





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	$(254.8\pm21.8)^\circ$	$(95.4\pm9.6)^\circ$	$(37.6\pm51.8)^\circ$

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	$(192.4\pm12.3)^\circ$	$(97.8\pm15.3)^\circ$	$(183.9\pm7.8)^\circ$

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.

A solution to $B \to \pi\pi$ puzzle in the SM

$B \to \pi\pi$ puzzle

γ	$(\lvert\widetilde{T}\rvert, \delta_{\widetilde{T}})$	$(\lvert\widetilde{C}\rvert, \delta_{\widetilde{C}})$	$\lvert P_{tc}\rvert$
65.5 ± 14.1	$(22.4 \pm 0.7, 36.0 \pm 22.6)$	$(15.8 \pm 4.1, -16.5 \pm 12.7)$	8.33 ± 4.34

Table 2: The results for the fit to the $B \to \pi\pi$ data alone. We obtained $\chi^2_{\min}/\mathrm{d.o.f} = 0.81/1$. Here $\widetilde{T} \equiv |\widetilde{T}|e^{i\delta_{\tilde{T}}} = T + P_{uc}$, $\widetilde{C} \equiv |\widetilde{C}|e^{i\delta_{\tilde{C}}} = C - P_{uc}$. The $\delta_{\widetilde{T}}$ ($\delta_{\widetilde{C}}$) is the strong phase of $\widetilde{T}$ ($\widetilde{C}$). The strong phase of P_{tc} is set to zero. The magnitudes and angles are in the unit of eV's and degrees, respectively.

$$\frac{|\widetilde{C}|}{|\widetilde{T}|} = 0.71 \pm 0.18$$

A solution to $B \to \pi\pi$ puzzle

- The T, C appear only in combinations of

$$\widetilde{T} = T + P_{uc}, \quad \widetilde{C} = C - P_{uc}$$

- If there is a constructive (destructive) interference between C (T) and P_{uc}, the puzzle is solved
- The P_{uc} can be extracted from the $B \to KK$. SB, PLB(2008)

A solution to $B \to \pi\pi$ puzzle and $B \to KK$

Mode	$\mathcal{B}[10^{-6}]$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
$B^+ \to K^+\overline{K^0}$	$1.36^{+0.29}_{-0.27}$	$0.12^{+0.17}_{-0.18}$	
$B^0 \to K^0\overline{K^0}$	$0.96^{+0.21}_{-0.19}$	$-0.58^{+0.73}_{-0.66}\pm0.04$ (Belle) $0.40\pm0.41\pm0.06$ (BaBar)	$-1.28^{+0.80}_{-0.73}{}^{+0.11}_{-0.16}$

Assuming flavor $SU(3)$ symmetry, we get P_{uc} from the $B \to KK$

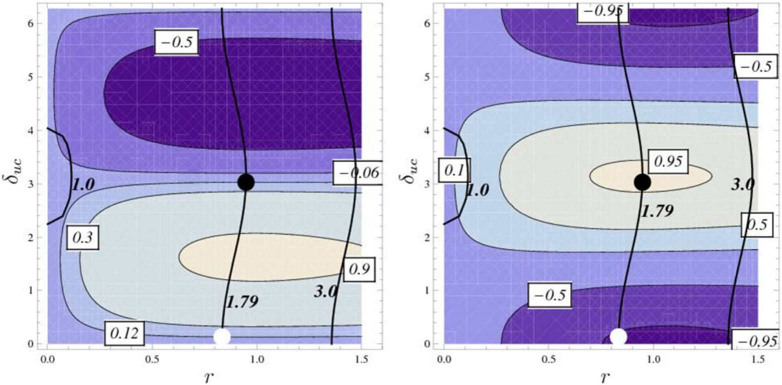
($r = |P_{uc}/P_{tc}|, \delta_{uc} = \arg(P_{uc}/P_{tc})$)

$$\mathcal{A}_{\rm CP}(B^{+(0)} \to K^{+(0)}\overline{K^0}) = \frac{2r\sin(\beta+\gamma)\sin\delta_{uc}}{1+r^2+2r\cos(\beta+\gamma)\cos\delta_{uc}},$$

$$\mathcal{S}_{\rm CP}(B^0 \to K^0\overline{K^0}) = -\frac{r^2\sin 2(\beta+\gamma)+2r\sin(\beta+\gamma)\cos\delta_{uc}}{1+r^2+2r\cos(\beta+\gamma)\cos\delta_{uc}}$$

$$R \equiv \frac{|A(B^+ \to K^+\overline{K^0})|^2 + |A(B^- \to K^-K^0)|^2}{2|P_{tc}|^2} = 1+r^2+2r\cos(\beta+\gamma)\cos\delta_{uc}$$

A solution to $B \to \pi\pi$ puzzle and $B \to KK$



- r and δ_{uc} can be determined with two-fold ambiguity.
- The black dot solution is favored in the SM.
- The ambiguity is lifted when S_{KK} is measured with more precision.

A solution to $B \to \pi\pi$ puzzle and $B \to KK$

γ	$(\lvert T\rvert, \delta_T)$	$(\lvert C\rvert, \delta_C)$
65.5 ± 14.1	$(28.7 \pm 4.8, 25.3 \pm 11.6)$	$(8.14 \pm 3.19, -26.12 \pm 30.6)$
65.5 ± 14.1	$(16.7 \pm 1.7, 47.5 \pm 36.6)$	$(22.3 \pm 7.1, -9.25 \pm 9.50)$
$(\lvert P_{tc}\rvert, \delta_{tc})$	$(\lvert P_{uc}\rvert, \delta_{uc})$	$\lvert C/T\rvert$
$(8.33 \pm 4.33, 0)$	$(7.89 \pm 6.82, 174 \pm 10)$	0.28 ± 0.15
$(8.33 \pm 4.34, 0)$	$(6.93 \pm 3.58, 7.42 \pm 11.2)$	1.34 ± 0.50

Table 3: The results for the fit to the $B \to \pi\pi$ and $B \to KK$ data. We obtained $\chi^2_{\min}/def = 1.5/2$. The strong phase of P_{tc} is set to 0. The magnitudes and angles are in the unit of eV's and degrees, respectively.

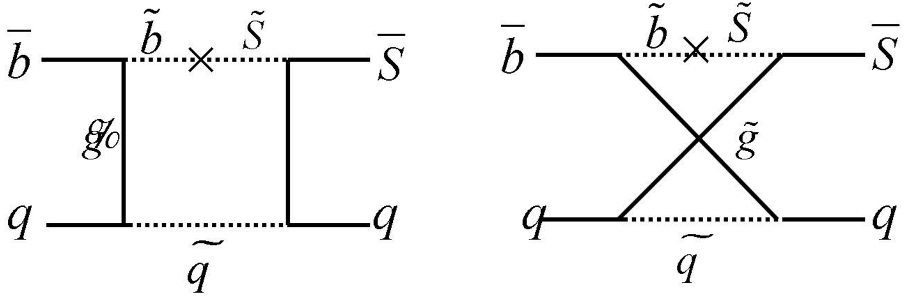
$B \to \pi K$ puzzle and NP models

$B \to \pi K$ puzzle and NP

- Two NP scenarios giving large EWP:
  - A SUSY scenario by Grossmann, Neubert, Kagan (GNK) SB, Imbeault, London (2008)
  - Leptophobic Z' SB, J. Jeon, C.S. Kim (2008)
- Other studies
  - Large 2-3 mixing in the u-quark sector. Khalil (2005), Khalil, Masiero, Murayama (2008)
  - R-parity violating SUSY Yang, Wang, Lu (2006)

SUSY GNK scenario

- $Z(\gamma)$-mediated EW-penguin in MSSM is suppressed.
- "Trojan penguin?" Grossmann, Neubert, Kagan(1999)



- Large enhancement in EWP is possible:

$$\frac{\alpha_s^2/M_{SUSY}^2}{\alpha_{ew}^2/M_W^2}$$

Structure of squark mass matrix

Squark mass matrix:

$K - \overline{K}$ $\quad B_d - \overline{B}_d$

$$M^2_{\tilde{d},LL} = \begin{pmatrix} \tilde{m}^{d,2}_{L_{11}} & 0 & 0 \\ 0 & \tilde{m}^{d,2}_{L_{22}} & \tilde{m}^{d,2}_{L_{23}} \\ 0 & \tilde{m}^{d,2}_{L_{32}} & \tilde{m}^{d,2}_{L_{33}} \end{pmatrix}, \quad M^2_{\tilde{d},LR(RL)} \equiv 0_{3\times 3}.$$

$$M^2_{\tilde{d},RR} = M^2_{\tilde{d},LL}\,|_{L\leftrightarrow R}$$

$B(B \to X_s \gamma)$

$$\Gamma_L M^2_{\tilde{d},LL} \Gamma_L^\dagger = \mathrm{diag}(m^2_{\tilde{d}_L}, m^2_{\tilde{s}_L}, m^2_{\tilde{b}_L}),$$

$$\Gamma_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L\, e^{i\delta_L} \\ 0 & -\sin\theta_L\, e^{-i\delta_L} & \cos\theta_L \end{pmatrix}.$$

$$\tilde{s}_L = \cos\theta_L\, \tilde{s}^0_L - \sin\theta_L\, e^{-i\delta_L}\, \tilde{b}^0_L$$

$$\tilde{b}_L = \sin\theta_L\, e^{i\delta_L}\, \tilde{s}^0_L + \cos\theta_L\, \tilde{b}^0_L$$

Large 2-3 mixing motivated by SUSY GUT.

S.B., T. Goto, Y. Okada, K. Okumura(01), Chang, Masiero, Murayama(02)

$$H_{\text{eff}}^{NP} = \frac{G_F}{\sqrt{2}} \left[\sum_{i,q=u,d} \left(c_i^q(\mu)\, O_i^q + \tilde{c}_i^q(\mu)\, \tilde{O}_i^q \right) + C_{8g}(\mu)\, Q_{8g} + \tilde{C}_{8g}(\mu)\, \tilde{Q}_{8g} \right] ,$$

$$\begin{aligned}
O_1^q &= (\bar{b}_\alpha s_\alpha)_{V-A}(\bar{q}_\beta q_\beta)_{V+A} \quad , & O_2^q &= (\bar{b}_\alpha s_\beta)_{V-A}(\bar{q}_\beta q_\alpha)_{V+A} \ , \\
O_3^q &= (\bar{b}_\alpha s_\alpha)_{V-A}(\bar{q}_\beta q_\beta)_{V-A} \quad , & O_4^q &= (\bar{b}_\alpha s_\beta)_{V-A}(\bar{q}_\beta q_\alpha)_{V-A} \ , \\
O_5^q &= (\bar{b}_\alpha q_\alpha)_{V-A}(\bar{q}_\beta s_\beta)_{V+A} \quad , & O_6^q &= (\bar{b}_\alpha q_\beta)_{V-A}(\bar{q}_\beta s_\alpha)_{V+A} \ , \\
Q_{8g} &= (g_s/8\pi^2) m_b \bar{b} \sigma_{\mu\nu}(1-\gamma_5) G^{\mu\nu} s \ .
\end{aligned}$$

$$\begin{aligned}
c_1^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[\frac{1}{18} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) - \frac{5}{18} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) + \frac{1}{2} A(x_{\tilde{b}_L \tilde{g}}) + \frac{2}{9} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\quad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}}) \\
c_2^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[\frac{7}{6} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) + \frac{1}{6} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) - \frac{3}{2} A(x_{\tilde{b}_L \tilde{g}}) - \frac{2}{3} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\quad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}}) \\
c_3^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[-\frac{5}{9} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_L \tilde{g}}) + \frac{1}{36} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_L \tilde{g}}) + \frac{1}{2} A(x_{\tilde{b}_L \tilde{g}}) + \frac{2}{9} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\quad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}})
\end{aligned}$$

Large SUSY contributions is possible when

- gluino mass is small
- $m^2_{\tilde{s}_{L,R}} \gg m^2_{\tilde{b}_{L,R}}$
- $\sin 2\theta_L$ or $\sin 2\theta_R$ not far below from 1
- $m^2_{\tilde{d}_R} \gg m^2_{\tilde{u}_R}$ cf. $m^2_{\tilde{d}_L} = m^2_{\tilde{u}_L}$ by $SU(2)$

Δm_s constraint

SB, JHEP(06)

- New operators in addition to the SM operator O_1 can be generated.

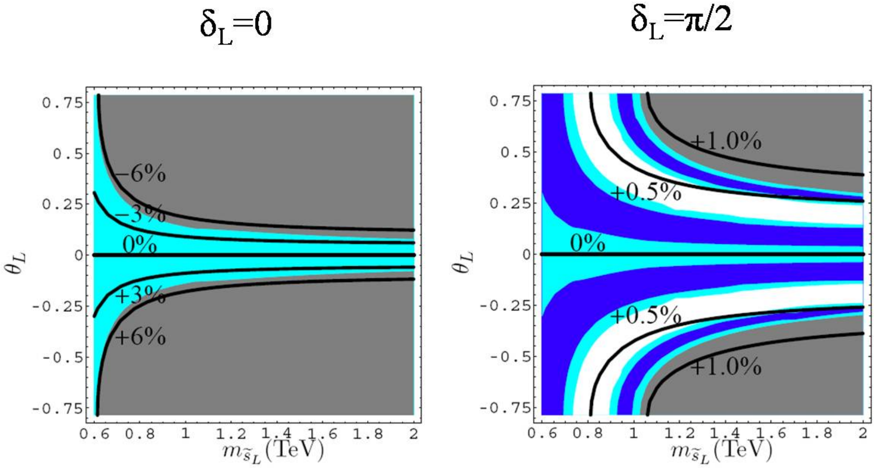
$$H_{\text{eff}} = \sum_{i=1}^{5} C_i O_i + \sum_{i=1}^{3} \widetilde{C}_i \widetilde{O}_i$$

$$\begin{aligned}
O_1 &= (\bar{s}_L \gamma_\mu b_L)\,(\bar{s}_L \gamma^\mu b_L),\\
O_2 &= (\bar{s}_R b_L)\,(\bar{s}_R b_L),\\
O_3 &= (\bar{s}_R^\alpha b_L^\beta)\,(\bar{s}_R^\beta b_L^\alpha),\\
O_4 &= (\bar{s}_R b_L)\,(\bar{s}_L b_R),\\
O_5 &= (\bar{s}_R^\alpha b_L^\beta)\,(\bar{s}_L^\beta b_R^\alpha),\\
\widetilde{O}_{i=1,\ldots 3} &= O_{i=1,\ldots 3}|_{L\leftrightarrow R}\cdots
\end{aligned}$$

$$\begin{aligned}
C_1^{\text{MSSM}} &= \frac{\alpha_s^2}{4m_{\tilde{g}}^2}\sin^2 2\theta_L e^{2i\delta_L}\left(f_1(x_{\tilde{b}_L,\tilde{g}},x_{\tilde{b}_L,\tilde{g}}) - 2f_1(x_{\tilde{s}_L,\tilde{g}},x_{\tilde{b}_L,\tilde{g}}) + f_1(x_{\tilde{s}_L,\tilde{g}},x_{\tilde{s}_L,\tilde{g}})\right)\\
C_{4(5)}^{\text{MSSM}} &= \frac{\alpha_s^2}{4m_{\tilde{g}}^2}\sin 2\theta_L \sin 2\theta_R e^{i(\delta_L+\delta_R)}\Big(f_{4(5)}(x_{\tilde{b}_R,\tilde{g}},x_{\tilde{b}_L,\tilde{g}}) - f_{4(5)}(x_{\tilde{b}_R,\tilde{g}},x_{\tilde{s}_L,\tilde{g}})\\
&\quad - f_{4(5)}(x_{\tilde{s}_R,\tilde{g}},x_{\tilde{b}_L,\tilde{g}}) + f_{4(5)}(x_{\tilde{s}_R,\tilde{g}},x_{\tilde{s}_L,\tilde{g}})\Big),\\
\widetilde{C}_1^{\text{MSSM}} &= C_1^{\text{MSSM}}|_{L\leftrightarrow R},
\end{aligned}$$

Δm_s constraint

$$m_{\tilde{g}} = 0.5\ (\text{TeV}),\ m_{\tilde{b}_L} = 0.5\ (\text{TeV})$$



$B \to X_s\gamma$ constraint $BR^{\text{exp}}(B \to X_s\gamma)/BR^{\text{SM}}(B \to X_s\gamma) = 1.06 \pm 0.13$

Δm_s constraint

- The constraints become more severe when both L and R exist simultaneously.
- The contribution to BR(b→sγ) is minor.

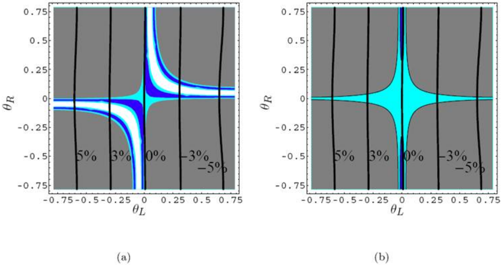


Figure 3: Contour plots for $|1+R|$ in (θ_L,θ_R) plane. $m_{\tilde{s}_L} = m_{\tilde{s}_R} = 0.6$ (TeV). (a) $\delta_L = \delta_R = 0$ (b) $\delta_L = 0, \delta_R = \pi/2$. We assume both LL and RR mixing exist. The rest is the same with figure 1.

$B \to \pi K$ in GNK scenario

- 12 SUSY parameters
- Generated 500,000 points in the region

$$300 \leq m_{\tilde{g}} \leq 2000\ \mathrm{GeV},$$
$$100 \leq m_{\tilde{q}} \leq 2000\ \mathrm{GeV},$$
$$-\pi/4 < \theta_{L,R} < \pi/4$$
$$-\pi < \delta_{L,R} < \pi$$
$$\gamma = 67.6^{+2.8^\circ}_{-4.5}$$

- Accepted a SUSY point as a ”solution” if $\chi^2_{\mathrm{min}} < 11.31$ (dof=9-4) (2 σ) of fitting P and T to the 9 data

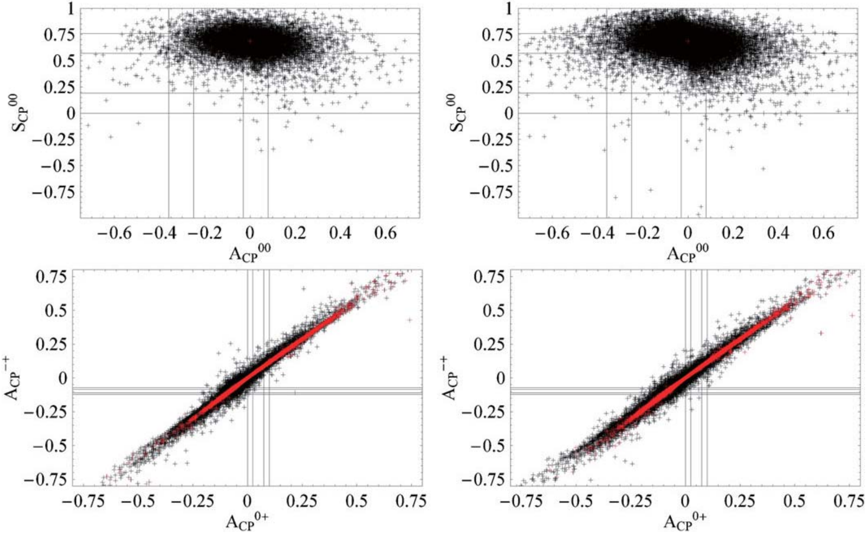
- Also imposing $\Delta m_s/\Delta m_s^{\rm SM} = 0.788 \pm 0.195$ at 2 σ, we get only small number of ”good” solutions.

Table 2

The number of points (out of 500 000) which satisfy $\chi^2_{\rm min}(B \to \pi K) < 11.31$, the Δm_s constraint within $\pm 2\sigma$, and both constraints. In the left table, only LL mixing is allowed, while in the right table, both LL and RR mixings are allowed

$\chi^2_{\rm min} < 11.31$	Δm_s	both
74	414357	15

$\chi^2_{\rm min} < 11.31$	Δm_s	both
102	92844	1



S_{CP}^{00}
A_{CP}^{00}
S_{CP}^{00}
A_{CP}^{00}
A_{CP}^{-+}
A_{CP}^{0+}
A_{CP}^{-+}
A_{CP}^{0+}

Leptophobic Z' scenario

- In the flipped $SU(5)$ GUT with

$$F = (\mathbf{10}, \frac{1}{2}) = \{Q, d^c, \nu^c\}, \quad \bar{f} = (\bar{\mathbf{5}}, -\frac{3}{2}) = \{L, u^c\}, \quad \ell^c = (\mathbf{1}, \frac{5}{2}) = \{e^c\}$$

- If Z' couples only to F, it becomes leptophobic. Lopez, Nanopoulos (97)
- The Z' coupling can be generation dependent and generate FCNC at tree-level.
- The couplings allow large CPV.
- Maximally violates the isospin symmetry in the right handed quarks. $\rightarrow$ New source of EW penguin.

- Lagrangian SB, Jeon, Kim (08)

$$\mathcal{L} = -\frac{g_2}{\cos\theta_W}\delta Z'_\mu \left(\overline{u}\gamma^\mu P_L \left[V_L^u \hat{c} V_L^{u\dagger} \right] u + \overline{d}\gamma^\mu P_L \left[V_L^d \hat{c} V_L^{d\dagger} \right] d + \overline{d}\gamma^\mu P_R \left[V_R^d \hat{c} V_R^{d\dagger} \right] d \right)$$

$$\mathcal{L}_{\rm FCNC}^{Z'} = -\frac{g_2}{2\cos\theta_W} \left[L_{sb}^{Z'} \overline{s}_L \gamma_\mu b_L Z'^\mu + R_{sb}^{Z'} \overline{s}_R \gamma_\mu b_R Z'^\mu \right] + h.c,$$

$$\mathcal{L}(Z'\overline{q}q) = -\frac{g_2}{\cos\theta_W}\delta\ Z'^\mu \left[\overline{u}\gamma_\mu c_L^u P_L u + \overline{d}\gamma_\mu (c_L^d P_L + c_R^d P_R) d \right]$$

- Δm_s constraint:

$$\Delta m_s^{\rm exp} = 17.77 \pm 0.10({\rm stat}) \pm 0.07({\rm syst})\ {\rm ps}^{-1}$$

$$\Delta m_s^{\rm SM}\Big|_{\rm (HP+JL)QCD} = 22.57^{+5.88}_{-5.22}\ {\rm ps}^{-1}$$

- Δm_s constraint (cont'd):

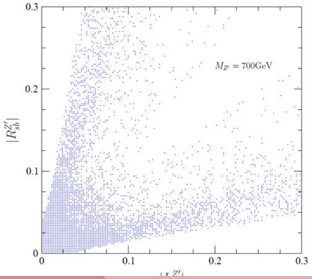
$$M_{12}^{s,Z'} = \frac{1}{3} M_{B_s} f_{B_s}^2 \left[\left(C_1(\mu_b) + \widetilde{C}_1(\mu_b) \right) B_1(\mu_b) + \frac{1}{4} \left(\frac{M_{B_s}}{m_b(\mu_b) + m_s(\mu_b)} \right)^2 \left(3C_4(\mu_b) B_4(\mu_b) + C_5(\mu_b) B_5(\mu_b) \right) \right]$$

$$C_1(M_{Z'}) = \frac{g_Z^2}{8M_{Z'}^2} \left(L_{sb}^{Z'} \right)^2,$$

$$\widetilde{C}_1(M_{Z'}) = \frac{g_Z^2}{8M_{Z'}^2} \left(R_{sb}^{Z'} \right)^2,$$

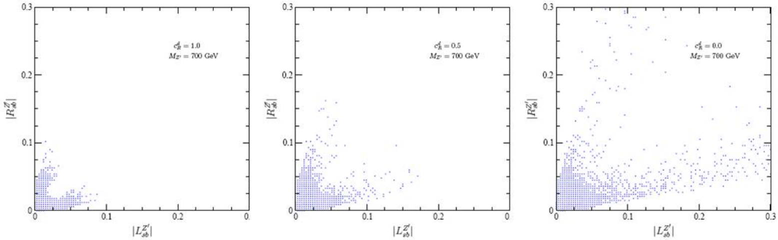
$$C_5(M_{Z'}) = \frac{g_Z^2}{8M_{Z'}^2} \left(-2 L_{sb}^{Z'} R_{sb}^{Z'} \right).$$

- Δm_s alone is not effective when both L and R couplings exist simultaneously.



Leptophobic Z'

- $BR(B \to \pi K)$ can be used to constrain (L, R) space.



- PQCD results (Li, Mishima, Sanda (05)) for the SM amp. and naive factorization for the NP amp. are used.

Leptophobic Z'

- The EWP can be enhanced considerably even after imposing Δm_s and $BR(B \to \pi K)$.

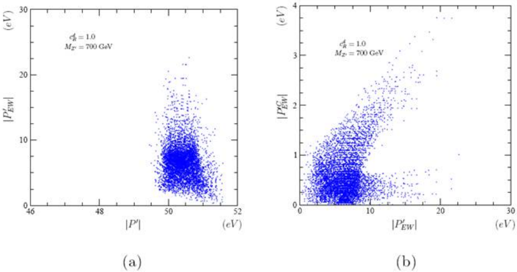
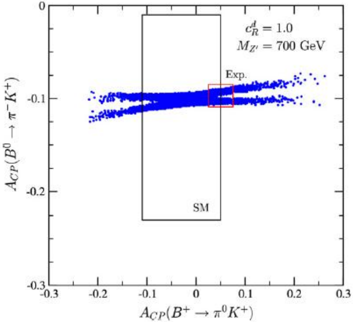
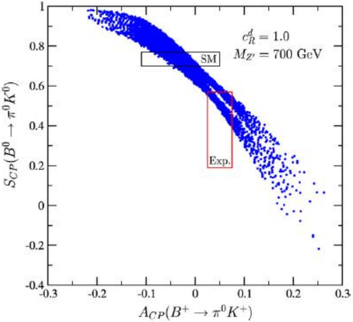


FIG. 2: The correlations between P'_{tc} and $P'_{\rm EW}$ (a) and between P'_{EW} and $P'^C_{\rm EW}$ (b) for $M_{Z'} = 700$ GeV and $c_R^d = 1$.

Leptophobic Z'

- Anomalies in S_{CP} and A_{CP} can be explained simultaneously.





Conclusions

Conclusions

- There are puzzles in the $B \to \pi\pi$ and $B \to \pi K$ decays.
- The $B \to \pi K$ puzzles:
  - 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.

Conclusions

- The $B \to \pi\pi$ puzzle can be solved in the SM.
- NP models solving $B \to \pi K$ puzzles:
  - The trojan penguin in the GNK model in the MSSM can marginally solve the puzzles.
  - The leptophobic Z' scenario can solve the puzzles naturally.