Direct CP Violation in B Decays

Michael Gronau
Technion, Haifa, Israel

FPCP07, Bled, May 13 2007

Outline

- Long but quick introduction: importance of DCPV, difficulty of calculating A_{CP}, a few potential $A_{CP} \neq 0$
- CP asymmetries in $B \to K\pi$
  - isospin sum rule, prediction for $A_{CP}(B^0 \to K^0\pi^0)$
  - $A_{CP}(B^0 \to K^+\pi^-) \neq A_{CP}(B^+ \to K^+\pi^0)$ puzzle?
  - implication of small $A_{CP}(B^+ \to K^+\pi^0)$
- CP asymmetries in $B \to \pi\pi$ vs $B \to K\pi$
  - success of flavor SU(3)
  - prediction for $A_{CP}(\pi^0\pi^0)$
- Role of DCPV in search for New Physics in $b \to s\bar{q}q$
- Conclusion

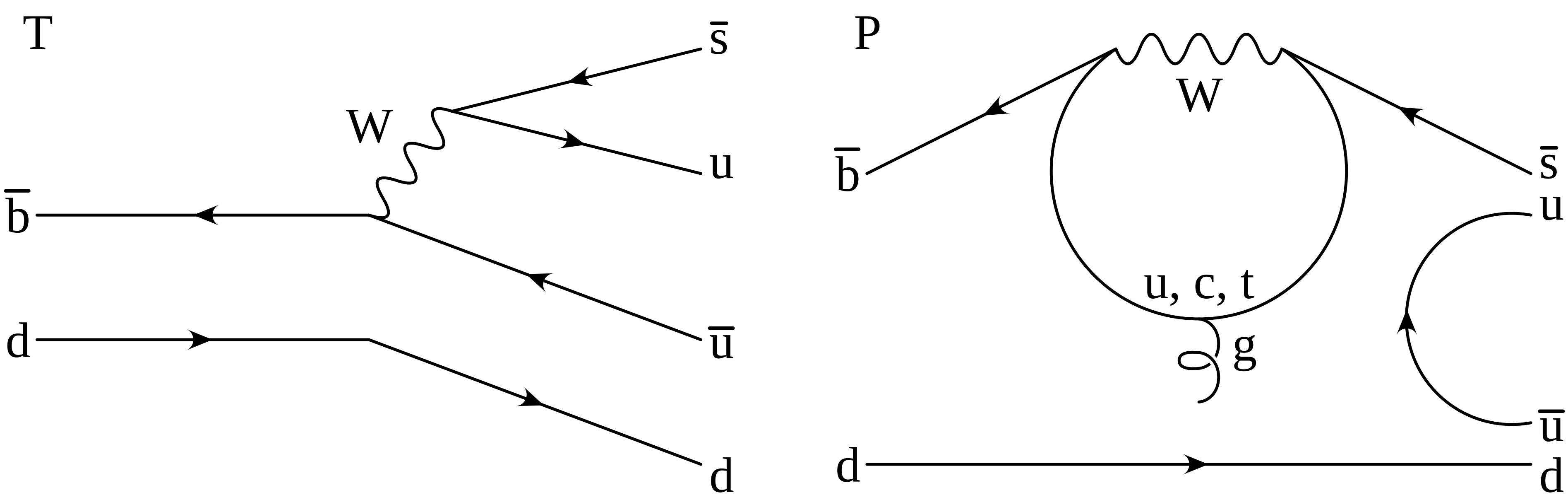
Importance of direct CP violation

Reminder (topics not to be discussed):

- DCPV is crucial for determining γ in $B \to DK$
- $A_{CP}(\pi^+\pi^-)$, $A_{CP}(\rho^+\rho^-)$ used for precise $\gamma = (72 \pm 6)^\circ$, agrees with $\gamma = (66 \pm 6)^\circ$ from $\frac{\Delta m_d}{\Delta m_s} = \frac{f_B^2 B_B}{f_{B_s}^2 B_{B_s}} \frac{|V_{td}|}{|V_{ts}|}^2$
- In general $A_{CP} \neq 0$; requires interference of two amplitudes with different weak and strong phases
- For large A_{CP} look for cases with two comparable amplitudes and large strong phases (resonant effects)
- Null tests: expect very small A_{CP} in certain decays
  $|A_{CP}(B^+ \to J/\psi K^+)| \ll 0.01$ HFAG: -0.024 ± 0.014
  $|A_{CP}(B^+ \to \pi^+\pi^0)| \ll 0.01$ 0.04 ± 0.05
  Nonzero asymmetries $\Rightarrow$ New Physics

Tree and Penguin amplitudes

$$B^0 \to K^+\pi^-$$



Difficulty of calculating A_{CP}

$$A(B^0 \to K^+\pi^-) = |P|e^{i\delta} + |T|e^{i\gamma} \qquad \delta = \text{strong}$$
$$A(\overline{B}^0 \to K^-\pi^+) = |P|e^{i\delta} + |T|e^{-i\gamma} \qquad \gamma = \text{weak}$$

$$A_{CP}(B^0 \to K^+\pi^-) \equiv \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$
$$= -\frac{2|T/P|\sin\delta\sin\gamma}{1+|T/P|^2+2|T/P|\cos\delta\cos\gamma}$$
$$|T/P| \ll 1: \qquad = -2|T/P|\sin\delta\sin\gamma \qquad + \mathcal{O}(|T/P|^2)$$

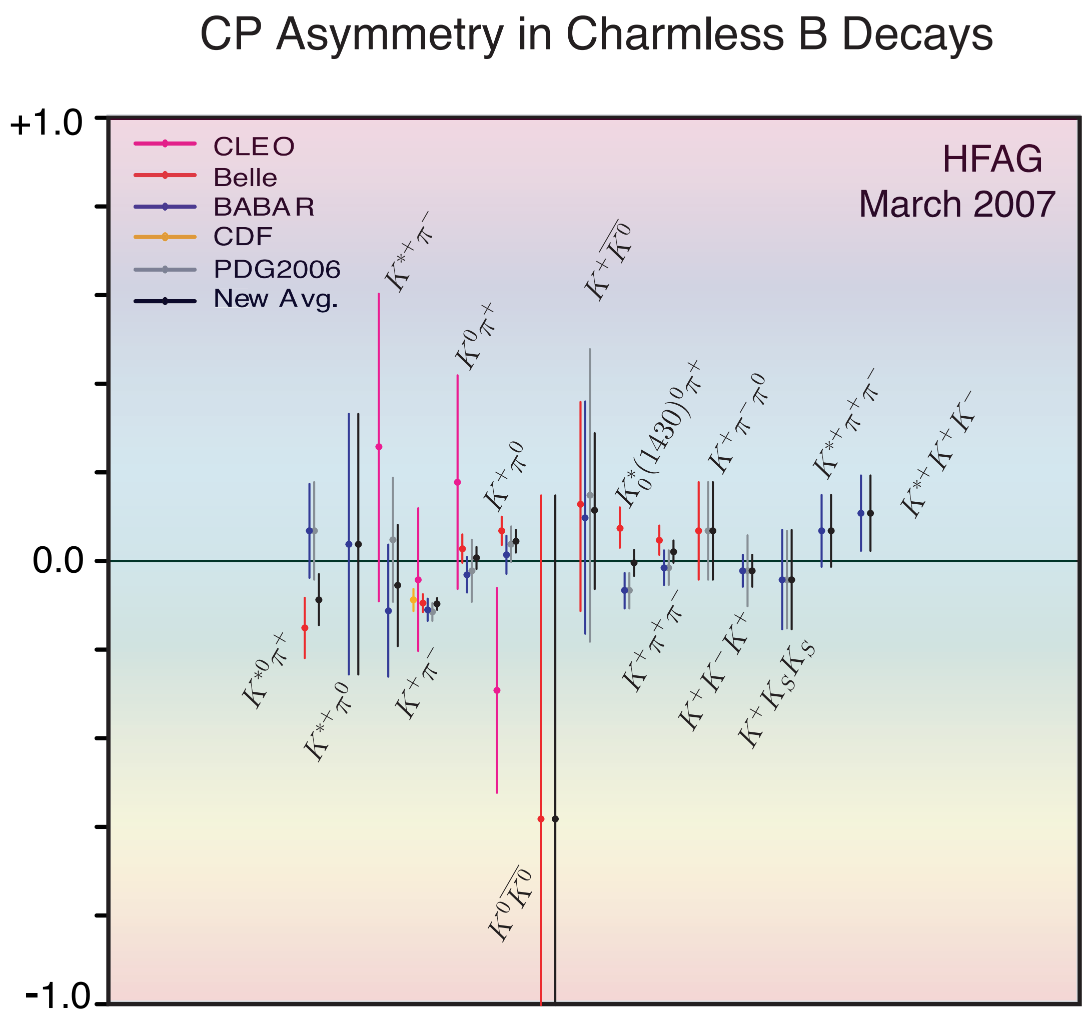
difficult to calculate strong phases δ: large uncertainties

QCDF: $1/m_b$ and α_s-suppressed

however

“long-distance charming penguin", $B \to DD_s \to K\pi$, “annihilation"

A sample of A_{CP} out of $\mathcal{O}(100)$



CP asymmetries (HFAG)

nonzero asymmetries

$B^0 \to K^+\pi^-$	$B^0 \to \pi^+\pi^-$	(Belle	Babar)
-0.097 ± 0.012	0.38 ± 0.07	(0.55 ± 0.09	0.21 ± 0.09)

related asymmetries

$B^+ \to K^+\pi^0$	$B^+ \to K^0\pi^+$	$B^0 \to K^0\pi^0$	$B^0 \to \pi^0\pi^0$
0.047 ± 0.026	0.009 ± 0.025	-0.12 ± 0.11	$0.36^{+0.33}_{-0.31}$

$\sim 3\sigma$ asymmetries

$\pi^+\eta$	$K^+\eta$	$K^{*0}\eta$	$K^+\rho^0$	$\rho^\pm\pi^\mp$
-0.19 ± 0.07	-0.29 ± 0.11	0.19 ± 0.05	$0.31^{+0.11}_{-0.10}$	-0.13 ± 0.04

3σ asymmetries $\sim \pm 0.2, \pm 0.3$

$A_{CP}(\pi^+\eta) = -0.19 \pm 0.07$: large $2P/(T+C)$

$A_{CP}(K^+\eta) = -0.29 \pm 0.11$: small $P \sim T$, dest. interference

$A_{CP}(K^+\rho^0) = 0.31^{+0.11}_{-0.10}$: interf. of P_V and large $T_V + C_P$

$A_{CP}(\rho^\pm\pi^\mp) = -0.13 \pm 0.04$: const. interf. $(P_V, T_V) - (P_P, T_P)$

$A_{CP}(K^{*0}\eta) = 0.19 \pm 0.05$: no good reason for “large" A_{CP}

All asym. except $K^{*0}\eta$ are very reasonable in flavor SU(3), QCD-factorization (SCET), PQCD; a few were anticipated

help study dynamics of hadronic charmless decays

CP asymmetries in $B \to K\pi$

A few simple facts about $B \to K\pi$ ($b \to s\bar{q}q$)

- $A(B \to K\pi) = B(\Delta I = 0) + A(\Delta I = 1) \qquad (u \leftrightarrow d)$

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

- Isospin quadrangle for amplitudes

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

- Penguin-dominance: $P(\Delta I = 0) \in B$, $\text{non-}P/P \sim 0.1$

(1) $\Gamma(K^0\pi^+) \approx \Gamma(K^+\pi^-) \approx 2\Gamma(K^+\pi^0) \approx 2\Gamma(K^0\pi^0)$

ratios consistent with 1 within 2σ: R, R_c, R_n (next)

(2) small CP asymmetries $A_{CP}(K^+\pi^-) = -0.097 \pm 0.012$

is first observed interference between P and non-P

R, R_c, R_n

$$R \equiv \frac{\Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^+ \to K^0\pi^+)} = 0.90 \pm 0.05$$

$$R_c \equiv \frac{2\Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^+ \to K^0\pi^+)} = 1.11 \pm 0.07$$

$$R_n \equiv \frac{\Gamma(B^0 \to K^+\pi^-)}{2\Gamma(B^0 \to K^0\pi^0)} = 0.97 \pm 0.07$$

consistent with one within 2σ

Sum rules for rates and asymmetries

Amplitude quadrangle relation and P-dominance imply

$$\mathbf{\Gamma}: \ \Gamma(K^+\pi^-) + \Gamma(K^0\pi^+) = 2[\Gamma(K^+\pi^0) + \Gamma(K^0\pi^0)][1 + (\frac{\text{non}P}{P})^2]$$

$$\mathbf{\Delta}: \Delta(K^+\pi^-) + \Delta(K^0\pi^+) = 2[\Delta(K^+\pi^0) + \Delta(K^0\pi^0)][1 + (\frac{\text{non}P}{P})^2]$$

few %

$$\Delta(K\pi) \equiv \Gamma(\bar{B} \to \bar{K}\bar{\pi}) - \Gamma(B \to K\pi)$$

$$\mathbf{\Delta} \Rightarrow A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \approx A_{CP}(K^+\pi^0) + A_{CP}(K^0\pi^0)$$

$\mathbf{\Gamma}-$SR holds experimentally within 5% expl. error

$\mathbf{\Delta}-$SR predicts: $A_{CP}(K^0\pi^0) = \mathbf{-0.140 \pm 0.043}$ (-0.12 ± 0.11)

error can be reduced by smaller errors in $A_{CP}(K^0\pi^+, K^+\pi^0)$

$\pm 0.025, \pm 0.026$

$A_{CP}(K^+\pi^0) \neq A_{CP}(K^+\pi^-)$ puzzle?

$A_{CP}(K^+\pi^-) = -0.097 \pm 0.012$ spectator d

difference $= 5\sigma$

$A_{CP}(K^+\pi^0) = 0.046 \pm 0.026$ spectator u

$A(K^+\pi^-) = P + T + ...$ $\sqrt{2}A(K^+\pi^0) = P + T + C + ...$ (next)

This would be a puzzle if $|C| \ll |T|$ but not if $|C| \sim |T|$

QCD calc. and SU(3) fits (excl. these asym.) find $|C| \sim |T|$

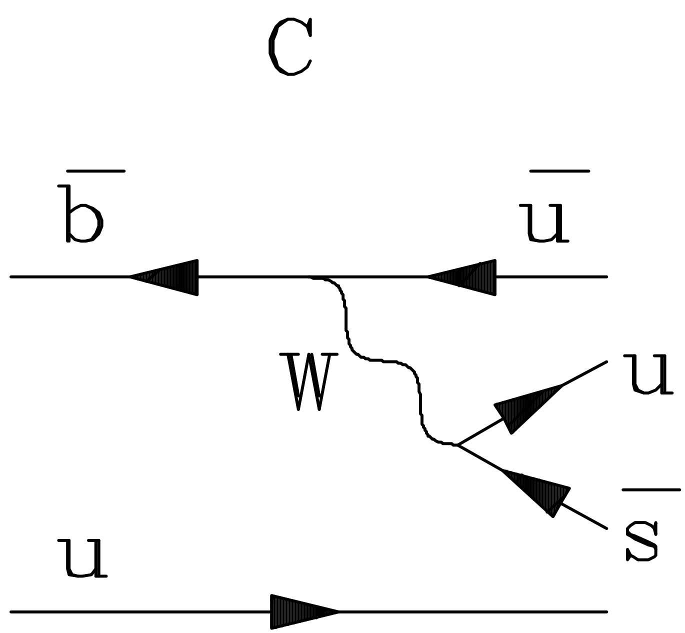
NO PUZZLE

Implication of 2 different asymmetries: $\mathbf{Arg(C/T) < 0}$ large

seems like a difficulty for QCD-factorization/SCET

Color-suppressed tree amplitude

$$B^+ \to K^+ \pi^0$$



Small $A_{CP}(K^+\pi^0)$ vs. small $R_c - 1$

$A(K^+\pi^0) = P + T + C$ $\qquad$ $A(K^0\pi^+) = P$

small $A_{CP}(K^+\pi^0)$ and small $R_c - 1 \equiv \frac{2\Gamma(K^+\pi^0)}{\Gamma(K^0\pi^+)} - 1$

0.046 ± 0.026 $\qquad$ 0.11 ± 0.07

looks like a problem

would not work without electroweak penguin contributions

Sum rule $\left(\frac{A_{CP}(K^+\pi^0)}{\sin\gamma}\right)^2 + \left(\frac{R_c - 1}{\cos\gamma - \delta_{\rm EW}}\right)^2 = (2r_c)^2 + \mathcal{O}(r_c^3)$

$\delta_{\rm EW} \equiv \frac{|P_{\rm EW}|}{|T+C|} = 0.60 \pm 0.05$ $\quad$ $r_c \equiv \frac{|T+C|}{|P|} = 0.20 \pm 0.02$ (incl. SU(3) brk)

$A_{CP}(K^+\pi^0) \simeq R_c - 1 \simeq 0 \quad \Rightarrow \quad \cos\gamma \simeq \delta_{\rm EW} \Rightarrow \gamma \simeq (53 \pm 4)^\circ$

with errors: $\gamma \leq 88^\circ$at 90% cl ($-0.05 < R_c$-$1 < 0.1 \Rightarrow \gamma < 71^\circ$)

Take a break

from

precise isospin sum rules for Γ, Δ

5%

to

less precise SU(3) relations for Δ

30%

CP asymmetries in $B \to K\pi, \pi\pi$

$$\Delta(K\pi) \equiv \Gamma(\bar{B} \to \bar{K}\bar{\pi}) - \Gamma(B \to K\pi)$$

Two simple relations: (1) $\Delta(K^+\pi^-) = -\Delta(\pi^+\pi^-)$

(1995) (2) $\Delta(K^0\pi^0) = -\Delta(\pi^0\pi^0)$

proof, slightly over-simplified ($\lambda \equiv V_{us}/V_{ud} = -V_{cd}/V_{cs}$)

$A(K^+\pi^-) = P + T$ $\quad$ $A(\pi^+\pi^-) = -\lambda P + \lambda^{-1} T + E + PA$

neglect $E + PA$ $[A(B^0 \to K^+K^-) \sim 1/m_b]$ $\Rightarrow$ equal CP rate asymmetries with opposite signs from PT interference

same for $\sqrt{2}A(K^0\pi^0) = P - C$ $\quad$ $\sqrt{2}A(\pi^0\pi^0) = -\lambda P - \lambda^{-1} C$

more rigorous proof includes $P_{\rm EW}$, and P_u terms in T and C

Success of flavor SU(3)

(1) $\Delta(K^+\pi^-) = -\Delta(\pi^+\pi^-)$

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

$$-1.88 \pm 0.24 = -1.96 \pm 0.37 \qquad (10^{-6})$$

works well, does not require SU(3) breaking

$\frac{f_K}{f_\pi}$ in $T\&P$: $\quad \Delta(K^+\pi^-) = -\left(\frac{f_K}{f_\pi}\right)^2 \Delta(\pi^+\pi^-)$

$$1.88 \pm 0.24 = 2.93 \pm 0.55 \qquad (10^{-6})$$

works less well

very likely: $\frac{f_K}{f_\pi}$ in T but not in P

must improve A_{CP} measurements to determine pattern of SU(3) breaking, useful for extracting a precise value of γ in $B^0 \to \pi^+\pi^-$

Large positive $A_{CP}(\pi^0\pi^0)$

(2) $\Delta(\pi^0\pi^0) = -\Delta(K^0\pi^0)$

$\Delta(K\pi)$ sum rule: $A_{CP}(K^0\pi^0) = -0.140 \pm 0.043$

prediction: $A_{CP}(\pi^0\pi^0) = -A_{CP}(K^0\pi^0)\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(\pi^0\pi^0)} = 1.07 \pm 0.38$

($0.36^{+0.33}_{-0.31}$)

SU(3) breaking $\frac{f_K}{f_\pi}$ in C (?) : $A_{CP}(\pi^0\pi^0) = 0.89 \pm 0.31$

large $A_{CP}(\pi^0\pi^0) > 0 \;\Rightarrow\; \mathcal{B}(B^0 \to \pi^0\pi^0) \ll \mathcal{B}(\overline{B}^0 \to \pi^0\pi^0)$

$\Rightarrow$ comparable sides in $\bar{B}$ triangle but **squashed** B triangle

discrete ambiguity disappears in the limit of **flat** B triangle

interesting implication on $B \to \pi\pi$ isospin analysis

DCPV in $b \to s\bar{q}q$ decays (New Physics?)

Asym. S and $C \equiv -A_{CP}$ in $B^0 \to X K_S(K_L)$

X	ϕ	π^0	η'	ω
$-\eta_{CP}S$	0.39 ± 0.18	0.33 ± 0.21	0.61 ± 0.07	0.48 ± 0.24
C	0.01 ± 0.13	0.12 ± 0.11	-0.09 ± 0.06	-0.21 ± 0.19
X	ρ^0	$f_0(980)$	K^+K^-	$K_S K_S$
$-\eta_{CP}S$	0.20 ± 0.57	0.42 ± 0.17	$0.58^{+0.18}_{-0.13}$	0.58 ± 0.20
C	0.64 ± 0.46	-0.02 ± 0.13	0.15 ± 0.09	-0.14 ± 0.15

$\sin 2\beta_{\rm eff} \equiv \langle -\eta_{CP} S \rangle = 0.53 \pm 0.05$ vs. $\sin 2\beta = 0.678 \pm 0.025$

Is this 2.6σ difference due to New Physics?

$\langle A_{CP} \rangle \equiv \langle -C \rangle = 0.01 \pm 0.04$; **Is this good news for SM?**

In the Standard Model S and C are process-dependent

Two comments

- When studying $\Delta S \equiv -\eta_{CP} S - \sin 2\beta \neq 0$ in $B^0 \to XK^0$ consider also the possibility $A_{CP} \equiv -C \neq 0$

  In the Standard Model ΔS **and** C **sit on a circle**, point on circle is determined by strong phase

$$\left(\frac{\Delta S}{\cos 2\beta}\right)^2 + C^2 = (2\xi \sin\gamma)^2 \qquad \xi \text{ depends on process}$$

- Once ΔS **and** C disagree with calculations of ξ beyond hadronic uncertainties, study source of New Physics

  To determine $\Delta I = 0, 1$ of NP operators, study also A_{CP} and A_I in **isospin-reflected** decays $B^+ \to XK^+$

$$A_I \equiv \frac{\Gamma(XK^+) - \Gamma(XK^0)}{\Gamma(XK^+) + \Gamma(XK^0)}$$

Conclusion

- No need to re-emphasize the importance of DCPV: γ in $B \to DK, B \to \pi^+\pi^-, \rho^+\rho^-$; $A_{CP}(\pi^+\pi^0) \neq 0 \Rightarrow$ NP
- A_{CP}'s are well-understood although difficult to calculate
- $A_{CP}(K^+\pi^0) \neq A_{CP}(K^+\pi^-)$ is not a puzzle
- $A_{CP}(K\pi)$ sum rule predicts $A_{CP}(K^0\pi^0) = -0.140 \pm 0.043$
- Small $A_{CP}(K^+\pi^0)$ and $R_c \approx 1$ imply a constraint on γ
- $A_{CP}(K^+\pi^-)/A_{CP}(\pi^+\pi^-)$ agrees with flavor SU(3), may fix pattern of SU(3) breaking which is useful for γ
- Flavor SU(3) predicts a large positive $A_{CP}(\pi^0\pi^0)$, which has an implication on the $B \to \pi\pi$ isospin analysis
- A_{CP}'s in $b \to s\bar{q}q$ play a role in studying New Physics