FPCP08, Taipei, May 5, 2008

Theoretical Review on CP Violation in Rare B Decays

Cheng-Wei Chiang

National Central University &
Academia Sinica

CP Violation in *B* Physics

Importance of CP Violation

- The Sakharov conditions for the observed Universe:
  - Baryon number violation;
  - CP violation; and
  - Departure from thermal equilibrium.

Sakharov 1967

- Studying and understanding the origin of CP violation in the SM is thus crucial to cosmology and discovering new physics.
- Recently, there is an attempt to connect current observations in *B* physics to cosmology by including fourth-generation fermions into the game.

Hou 2008

KM Mechanism

- The couplings between the up-type and down-type quarks are described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix within the SM.

Cabibbo 1963; Kobayashi & Maskawa 1973

Wolfenstein 1983

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$
$$= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \boxed{A\lambda^3}(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \boxed{A\lambda^3}[(1-\bar{\rho}) - i\bar{\eta}] & -A\lambda^2 & 1 \end{pmatrix}$$

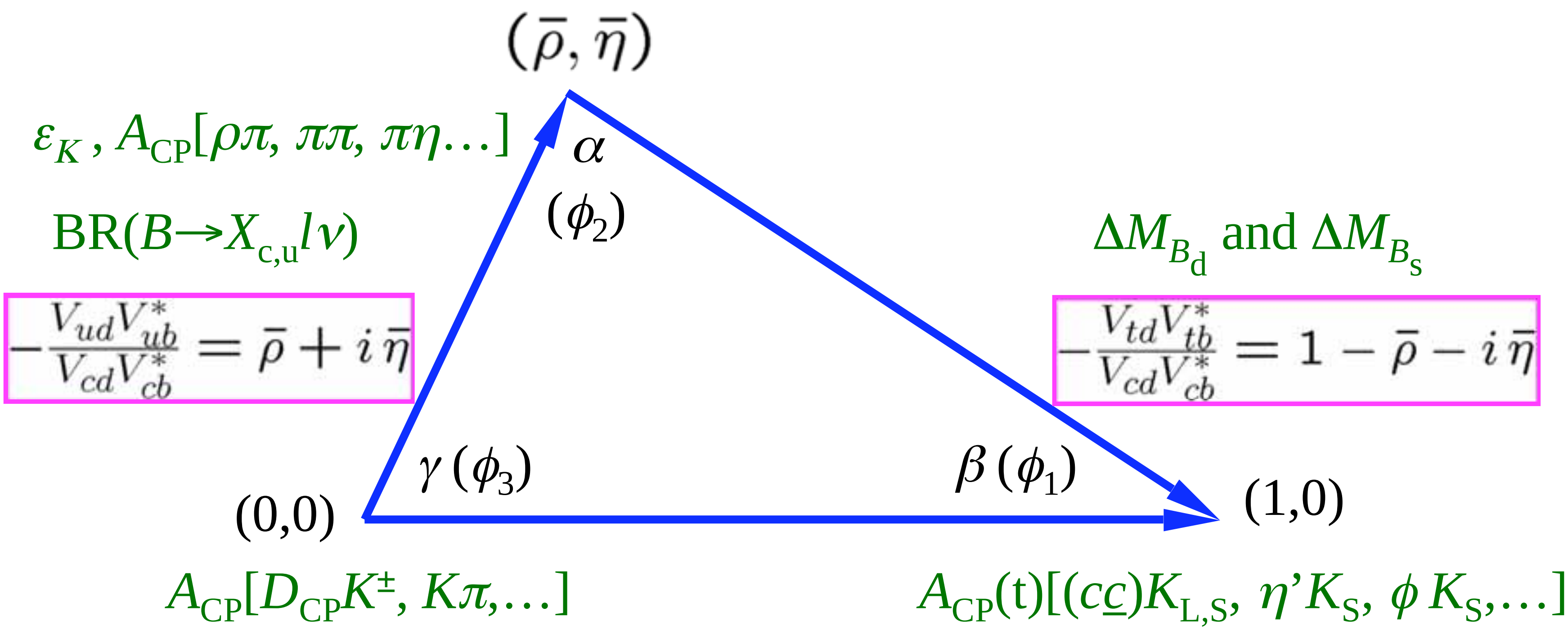
- Using the Wolfenstein parameterization, CP violation is encoded by the parameter η.
- Among the elements, V_{ub} and V_{td} carry the largest weak phases, but are difficult to extract due to their smallness.

Unitarity Triangle

- Unitarity relation for V_{ub} and V_{td} :

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

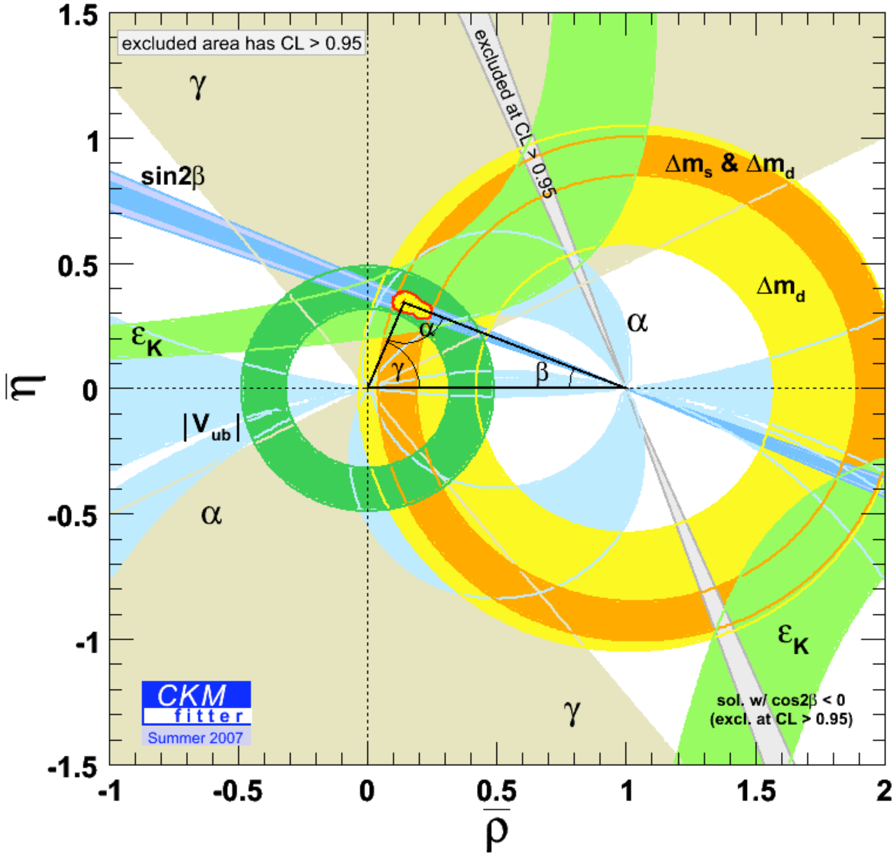
It can be visualized as a triangle on a complex plane whose *area* characterizes CPV.



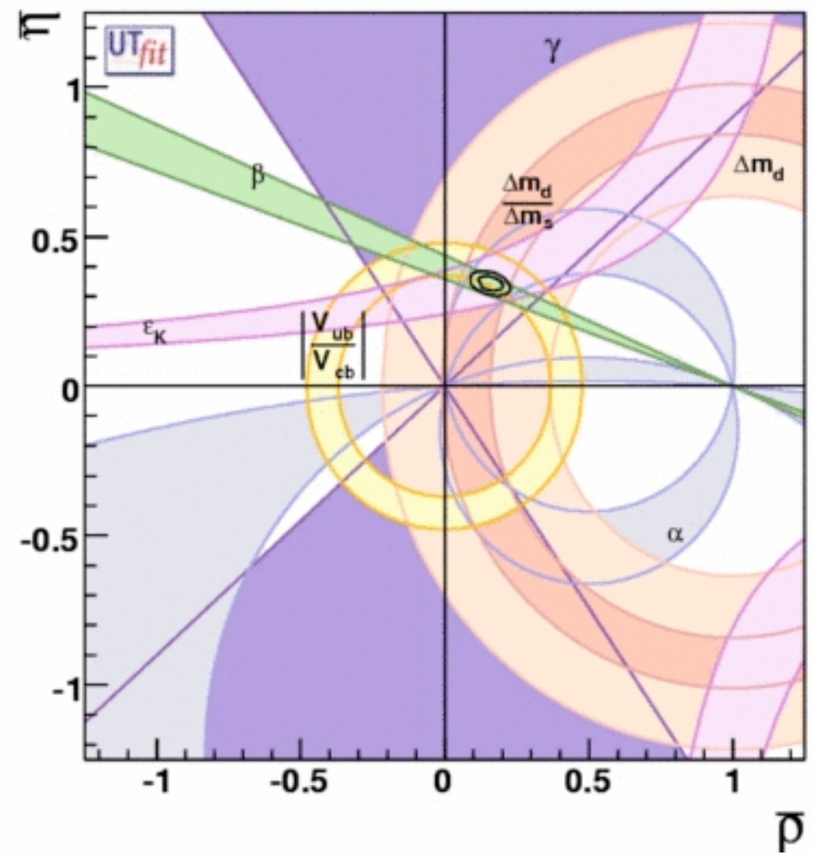
Experimental Constraints

- The state-of-art global fits for the unitarity triangle are:

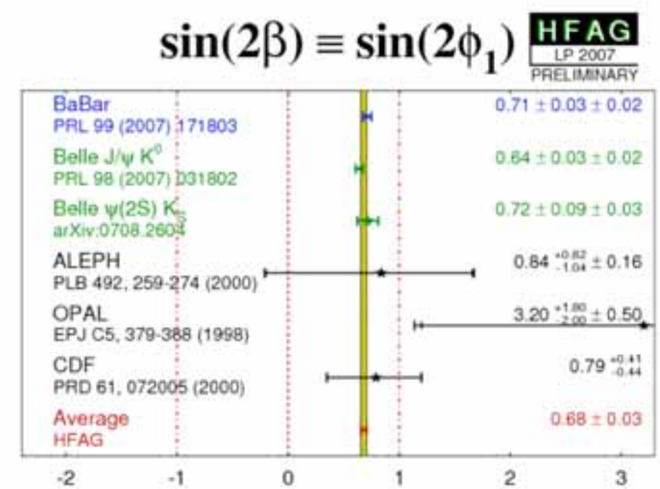
CKMfitter 2007 Winter
http://ckmfitter.in2p3.fr/



UTFit 2008 Spring
http://utfit.roma1.infn.it/



Observed CP Violation in Rare *B* Decays



- The *indirect* CP violation in the *B* system has been first established in 2001, and is now measured at a precision <5%.

See Chua's talk today

- The *direct* CP violation in the *B* system has first been observed in the $B_d \to K^+\pi^-$ decay in 2004, a result of interference between tree and QCD-penguin amplitudes.
- Currently, DCPV observed at the 3σ level or more:

HFAG 2008 Spring

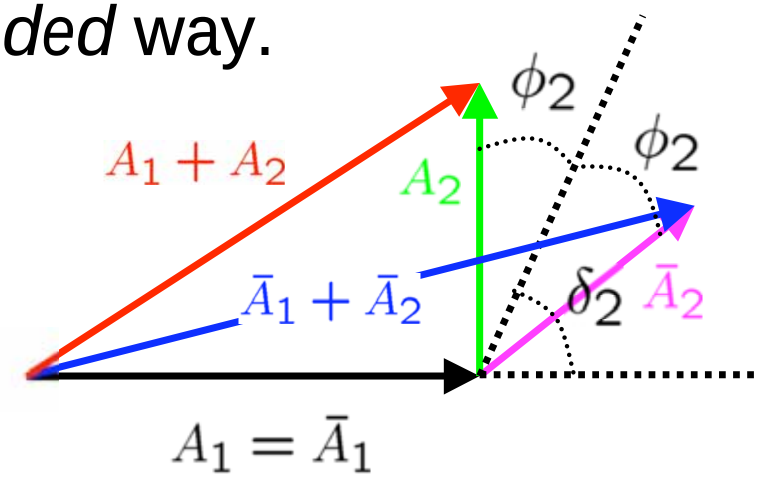
$\mathcal{A}_{CP}(K^+\pi^-)$	-0.097 ± 0.012	8.1σ
$\mathcal{A}_{CP}(\pi^+\pi^-)$	0.38 ± 0.07	5.4σ
$\mathcal{A}_{CP}(K^{*0}\eta)$	0.19 ± 0.05	3.8σ
$\mathcal{A}_{CP}(\rho^0 K^+)$	0.37 ± 0.11	3.4σ
$\mathcal{A}_{CP}(\rho^\pm \pi^\mp)$	-0.13 ± 0.04	3.3σ
$\mathcal{A}_{CP}(\eta K^+)$	-0.27 ± 0.09	3σ

Importance of Rare Decays

- Charmless two-body hadronic B decay modes are often sensitive to V_{td} (mixing) and/or V_{ub} (decay).
- Information of weak phases in the UT are often cleanly coded in their CP-averaged rates and CP asymmetries.
- These decays are thus charmful and can play a more important role in fixing the UT.
- With increasing precision on the BR's and CPA's, it is possible to provide an additional constraint on the (ρ,η) vertex and/or some hints for new physics via a global fit.

Direct CP Asymmetry

- Strong interactions contribute additional phases to decay amplitudes in a *flavor-blinded* way.
- Consider rate CP asymmetry of modes with the amplitudes:



$$A(B \to f) = A_1 + A_2 e^{i(\phi_2 + \delta_2)}$$
$$A(\overline{B} \to \overline{f}) = A_1 + A_2 e^{i(-\phi_2 + \delta_2)}$$
$$\Rightarrow \quad \mathcal{A}_{CP} = \frac{2A_1 A_2 \sin\phi_2 \, \sin\delta_2}{A_1^2 + A_2^2 + 2A_1 A_2 \cos\phi_2 \cos\delta_2}$$

CP-averaged rate

- A sizeable CPA for experimental observation requires the interference of at least *two* comparable amplitudes with *large relative* strong and weak phases.

Difficulty in Perturbative Approach

- The program of studying CP-violating phases is partly impeded by the lack of full dynamical understanding in hadronic physics (including both strong phases and hadronic ME's).

See QCDF, pQCD & SCET talks on 5/6 morning

- Strong phases originating from short-distance physics are known to be small.

Bander, Silverman & Soni 1979

- Large strong phases are usually obtained from model calculations of final-state rescattering effects.

Chua, Hou & Yang 2003; Cheng, Chua & Soni 2005

- An alternative (non-perturbative) approach is to employ flavor SU(3) symmetry principle to relate / reduce hadronic parameters.

Zeppenfeld 1981; Chau & Cheng 1986, 1987, 1991; Savage & Wise 1989; Grinstein & Lebed 1996; Gronau et. al. 1994, 1995, 1995

Flavor SU(3) Symmetry

- Treat (u,d,s) as a triplet of the group.
- Except for weak couplings, the underlying strong dynamics should not distinguish u, d, and s in diagrams with the same flavor topology.
- Relate two types of rare decay amplitudes and associated strong phases using the symmetry:

  strangeness-conserving ($\Delta S = 0$, $b \rightarrow q\underline{q}d$); and

  strangeness-changing ($|\Delta S| = 1$, $b \rightarrow q\underline{q}s$).
- Because of CKM factors, the former type is dominated by the color-allowed tree amplitude; whereas the latter type is dominated by the QCD-penguin amplitudes.

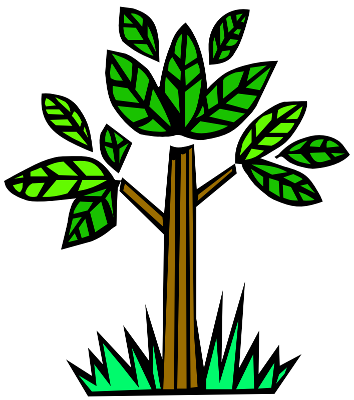
Questions

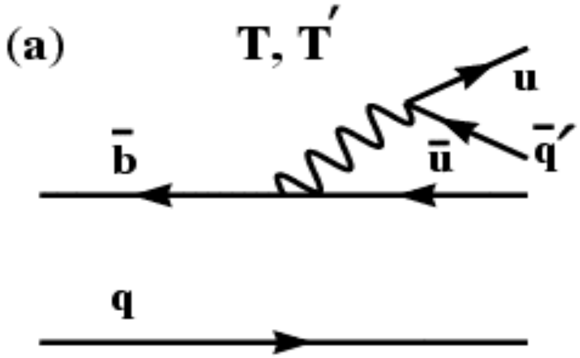
- Do the CP asymmetries along with the branching ratios of these rare *B* decays currently provide a coherent picture (instead of looking at mode by mode)?
- Is it consistent with what we have learned from other processes (*e.g.*, charmed *B* decays)?

Flavor SU(3) Global Fits

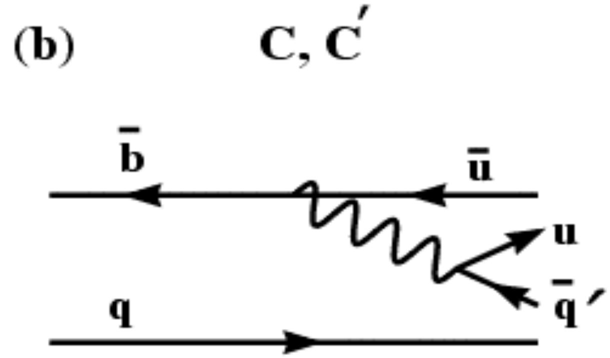
Flavor Diagrams

- The following flavor diagrams are included in our analysis.



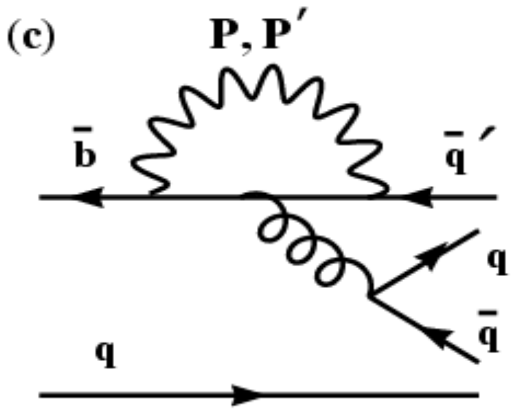


tree (external W emission)

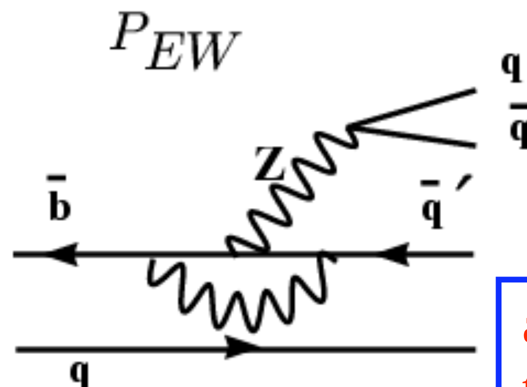


color-suppressed (internal W emission)

q = u,d,s
q′= d,s



QCD (strong) penguin
(internal gluon emission)



EW penguin

always appears together with C in decay amps

Flavor Diagrams

- The physical amplitudes are then

SU(3)-breaking ~ f_K/f_π?

$$t \equiv Y_{db}^u T \qquad t' \equiv Y_{sb}^u \xi_t T$$

$$c \equiv Y_{db}^u C - (Y_{db}^u + Y_{db}^c) P_{EW} \qquad c' \equiv Y_{sb}^u \xi_c C - (Y_{sb}^u + Y_{sb}^c) P_{EW}$$

$$p \equiv -(Y_{db}^u + Y_{db}^c) P \qquad p' \equiv -(Y_{sb}^u + Y_{sb}^c) \xi_p P$$

  where $Y_{qb}^{q'} = V_{q'q} V_{q'b}^*$, and each amp has its strong phase.
- The CKM factors have been explicitly pulled out.
- Unprimed amplitudes are used for strangeness-conserving ($\Delta S = 0$) transitions and primed amplitudes for strangeness-changing ($|\Delta S| = 1$) ones.
- In the case of *VP* decays, we associate a subscript *P* or *V* to indicate which meson the spectator quark ends up with.

PP Modes

Mode		Flavor Amplitude	BR	$\mathcal{A}_{CP}$
$B^- \to$	$\pi^-\pi^0$	$-\frac{1}{\sqrt{2}}(t+c)$	5.7 ± 0.5	0.04 ± 0.05
	$K^-\overline{K}^0$	p	1.4 ± 0.3	0.12 ± 0.18
	$\pi^-\eta$	$-\frac{1}{\sqrt{3}}(t+c+2p+s)$	4.4 ± 0.4	-0.19 ± 0.07
	$\pi^-\eta'$	$\frac{1}{\sqrt{6}}(t+c+2p+4s)$	2.6 ± 0.8	0.15 ± 0.15
$\bar{B}^0 \to$	K^+K^-	$-(e+pa)$	0.07 ± 0.11	-
	$K^0\overline{K}^0$	p	1.0 ± 0.2	-
	$\pi^+\pi^-$	$-(t+p)$	5.2 ± 0.2	0.39 ± 0.19
				-0.58 ± 0.09
	$\pi^0\pi^0$	$\frac{1}{\sqrt{2}}(-c+p)$	1.3 ± 0.2	0.36 ± 0.32
	$\pi^0\eta$	$-\frac{1}{\sqrt{6}}(2p+s)$	0.60 ± 0.46	-
	$\pi^0\eta'$	$\frac{1}{\sqrt{3}}(p+2s)$	1.2 ± 0.7	-
	$\eta\eta$	$\frac{1}{3\sqrt{2}}(2c+2p+2s)$	< 1.2	-
	$\eta\eta'$	$-\frac{1}{3\sqrt{2}}(2c+2p+5s)$	< 1.7	-
	$\eta'\eta'$	$\frac{1}{3\sqrt{2}}(c+p+4s)$	< 10	-
$\bar{B}^0_s \to$	$K^+\pi^-$	$-(t+p)$	< 5.6	-
	$K^0\pi^0$	$-\frac{1}{\sqrt{2}}(-c+p)$	-	-
	$\bar{K}^0\eta$	$-\frac{1}{\sqrt{3}}(c+s)$	-	-
	$\bar{K}^0\eta'$	$\frac{1}{\sqrt{6}}(c+3p+4s)$	-	-

Mode		Flavor Amplitude	BR	$\mathcal{A}_{CP}$
$B^- \to$	$\pi^-\bar{K}^0$	p'	23.1 ± 1.0	0.01 ± 0.02
	π^0K^-	$-\frac{1}{\sqrt{2}}(p'+t'+c')$	12.8 ± 0.6	0.05 ± 0.03
	$K^-\eta$	$-\frac{1}{\sqrt{3}}(s'+t'+c')$	2.2 ± 0.4	-0.29 ± 0.11
	$K^-\eta'$	$\frac{1}{\sqrt{6}}(3p'+4s'+t'+c')$	69.7 ± 2.8	0.03 ± 0.02
$\bar{B}^0 \to$	π^+K^-	$-(p'+t')$	19.7 ± 0.6	-0.098 ± 0.015
	$\pi^0\bar{K}^0$	$\frac{1}{\sqrt{2}}(p'-c')$	10.0 ± 0.6	-0.12 ± 0.11
				0.33 ± 0.21
	$\bar{K}^0\eta$	$-\frac{1}{\sqrt{3}}(s'+c')$	1.2 ± 0.3	-
	$\bar{K}^0\eta'$	$\frac{1}{\sqrt{6}}(3p'+4s'+c')$	64.9 ± 4.4	-0.09 ± 0.06
				0.60 ± 0.08
$\bar{B}^0_s \to$	K^+K^-	$-(p'+t')$	34 ± 9	-
	$K^0\overline{K}^0$	p'	-	-
	$\pi^+\pi^-$	$-(e'+pa')$	< 1.7	-
	$\pi^0\pi^0$	$\frac{1}{\sqrt{2}}(e'+pa')$	< 2.1	-
	$\pi^0\eta$	$-\frac{1}{\sqrt{6}}c'$	-	-
	$\pi^0\eta'$	$-\frac{1}{\sqrt{3}}c'$	-	-
	$\eta\eta$	$-\frac{1}{3\sqrt{2}}(2p'-2s'-2c')$	-	-
	$\eta\eta'$	$\frac{1}{3\sqrt{2}}(4p'+2s'-c')$	-	-
	$\eta'\eta'$	$\frac{1}{3\sqrt{2}}(4p'+8s'+2c')$	-	-

ICHEP 06

Results of Fits to $\pi\pi$, $K\pi$, and KK

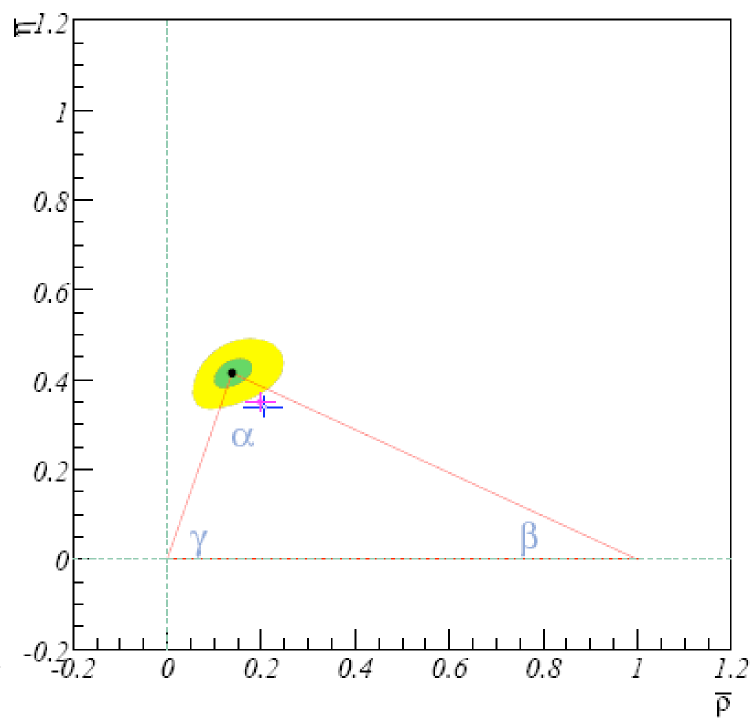
- Results are quite robust against SU(3) breaking.
- Prefer f_K / f_π for T and C, agreeing with factorization.
- Large relative size and strong phase between C and T.

Chiang & Zhou 2006

Parameter	Scheme 1	Scheme 2	Scheme 3	Scheme 4
$\bar\rho$	$0.139^{+0.042}_{-0.037}$	$0.134^{+0.041}_{-0.036}$	$0.134^{+0.041}_{-0.036}$	$0.133^{+0.039}_{-0.035}$
$\bar\eta$	0.401 ± 0.030	0.403 ± 0.031	0.404 ± 0.031	0.399 ± 0.031
A	0.807 ± 0.013	0.807 ± 0.013	0.807 ± 0.013	0.807 ± 0.013
$\|T\|$	$0.573^{+0.055}_{-0.047}$	$0.575^{+0.055}_{-0.047}$	$0.574^{+0.055}_{-0.047}$	$0.582^{+0.056}_{-0.049}$
$\|C\|$	0.371 ± 0.050	0.364 ± 0.050	0.364 ± 0.049	0.372 ± 0.051
δ_C	-57.6 ± 10.3	-55.9 ± 10.7	-55.8 ± 10.2	-56.3 ± 10.1
$\|P\|$	0.121 ± 0.002	0.122 ± 0.002	0.122 ± 0.002	0.117 ± 0.008
δ_P	-22.7 ± 4.0	-18.8 ± 3.2	-19.3 ± 3.2	$-18.6^{+3.2}_{-3.5}$
$\|P_{EW}\|$	$0.011^{+0.006}_{-0.003}$	$0.011^{+0.006}_{-0.003}$	$0.011^{+0.005}_{-0.003}$	$0.011^{+0.004}_{-0.003}$
$\delta_{P_{EW}}$	$-4.3^{+34.1}_{-50.6}$	$2.2^{+32.0}_{-49.3}$	$-10.0^{+37.2}_{-45.3}$	-15.1 ± 39.9
ξ	1(fixed)	1(fixed)	1(fixed)	$1.04^{+0.08}_{-0.07}$
$\chi^2_{\rm min}/dof$	18.9/12	18.0/12	16.4/12	16.1/11

Table 3: Fit results of the parameters for the $\pi\pi$, πK, and KK modes in Schemes 1 through 4 defined in the text along with the minimal χ^2 value. The amplitudes are given in units of 10^4 eV. (JHEP 2006 work.)

Preferred set



Predictions for $B_{u,d}$ Decays

$\propto p - c$; exp: 1.31±0.21

result of comparable amps

$\propto p' + t'$; exp: –0.097±0.012

$\propto p' + t' + c'$; exp: 0.05±0.03

$\propto p - c$, large S_{CP} predicted

$\propto p' - c'$; exp: 0.38±0.19

Observable	Scheme 1	Scheme 2	Scheme 3	Scheme 4
$Br(\pi^+\pi^-)$	5.4 ± 1.1	5.4 ± 1.0	5.3 ± 1.0	5.3 ± 1.1
$Br(\pi^0\pi^0)$	1.6 ± 0.4	1.6 ± 0.4	1.6 ± 0.4	1.5 ± 0.4
$Br(\pi^-\pi^0)$	5.3 ± 1.2	5.4 ± 1.2	5.4 ± 1.2	5.4 ± 1.3
$Br(\pi^+K^-)$	20.2 ± 1.0	20.1 ± 1.1	20.1 ± 1.1	20.3 ± 4.3
$Br(\pi^0\bar{K}^0)$	9.9 ± 1.0	9.9 ± 1.0	10.0 ± 0.9	10.1 ± 2.3
$Br(\pi^-\bar{K}^0)$	23.0 ± 1.1	23.1 ± 1.1	23.1 ± 1.1	23.4 ± 4.8
$Br(\pi^0K^-)$	12.0 ± 1.2	12.1 ± 1.2	12.0 ± 1.1	12.2 ± 2.5
$Br(K^+K^-)$	0	0	0	0
$Br(K^0\bar{K}^0)$	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.2
$Br(K^-\bar{K}^0)$	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.0 ± 0.2
$\mathcal{A}(\pi^+\pi^-)$	0.32 ± 0.07	0.27 ± 0.06	0.28 ± 0.06	0.26 ± 0.06
$\mathcal{A}(\pi^0\pi^0)$	0.47 ± 0.15	0.49 ± 0.15	0.49 ± 0.14	0.50 ± 0.14
$A_{CP}(\pi^-\pi^0)$	-0.01 ± 0.04	-0.02 ± 0.03	-0.01 ± 0.03	-0.01 ± 0.03
$A_{CP}(\pi^+K^-)$	-0.08 ± 0.02	-0.09 ± 0.02	-0.09 ± 0.02	-0.09 ± 0.02
$\mathcal{A}(\pi^0K_S)$	-0.07 ± 0.03	-0.08 ± 0.02	-0.09 ± 0.03	-0.10 ± 0.03
$A_{CP}(\pi^-\bar{K}^0)$	0	0	0	0
$A_{CP}(\pi^0K^-)$	0.00 ± 0.03	0.00 ± 0.03	0.01 ± 0.04	0.02 ± 0.04
$A_{CP}(K^+K^-)$	0	0	0	0
$\mathcal{A}(K^0\bar{K}^0)$	0	0	0	0
$A_{CP}(K^-\bar{K}^0)$	0	0	0	0
$\mathcal{S}(\pi^+\pi^-)$	-0.580 ± 0.130	-0.585 ± 0.130	-0.584 ± 0.130	-0.565 ± 0.141
$\mathcal{S}(\pi^0\pi^0)$	0.814 ± 0.109	0.812 ± 0.108	0.810 ± 0.106	0.786 ± 0.113
$\mathcal{S}(\pi^0K_S)$	0.851 ± 0.042	0.850 ± 0.041	0.861 ± 0.041	0.858 ± 0.042
$\mathcal{S}(K^0\bar{K}^0)$	-0.000 ± 0.014	-0.000 ± 0.014	-0.000 ± 0.014	-0.000 ± 0.015

BR in units of 10^{-6}

Predictions for B_s Decays

$\propto e' + pa'$
exp: $(0.53 \pm 0.51) \times 10^{-6}$

exp: $(5.27 \pm 1.27) \times 10^{-6}$

exp: $(24.4 \pm 4.8) \times 10^{-6}$

$\propto p'$; test SU(3)

$\propto t + p$;
exp: 0.39 ± 0.17

$\propto p - c$, related to $B_d \to \pi^0 \pi^0$

$\propto t' + p'$, related to $B_d \to \pi^+ K^-$

Observable	Scheme 1	Scheme 2	Scheme 3	Scheme 4
$Br(\pi^+\pi^-)$	0	0	0	0
$Br(\pi^0\pi^0)$	0	0	0	0
$Br(\pi^+K^-)$	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0
$Br(\pi^0K^0)$	1.5 ± 0.3	1.5 ± 0.3	1.5 ± 0.3	1.4 ± 0.3
$Br(K^+K^-)$	18.9 ± 1.0	18.8 ± 1.0	18.8 ± 1.0	19.0 ± 4.0
$Br(K^0\bar{K}^0)$	20.0 ± 1.0	20.2 ± 1.0	20.1 ± 1.0	20.4 ± 4.2
$\mathcal{A}(\pi^+\pi^-)$	0	0	0	0
$\mathcal{A}(\pi^0\pi^0)$	0	0	0	0
$A_{CP}(\pi^+K^-)$	0.32 ± 0.07	0.27 ± 0.06	0.28 ± 0.06	0.26 ± 0.06
$\mathcal{A}(\pi^0K_S)$	0.47 ± 0.15	0.49 ± 0.15	0.49 ± 0.14	0.50 ± 0.14
$\mathcal{A}(K^+K^-)$	-0.08 ± 0.02	-0.09 ± 0.02	-0.09 ± 0.02	-0.09 ± 0.02
$\mathcal{A}(K^0\bar{K}^0)$	0	0	0	0
$\mathcal{S}(\pi^+\pi^-)$	0	0	0	0
$\mathcal{S}(\pi^0\pi^0)$	0	0	0	0
$\mathcal{S}(\pi^0K_S)$	0.340 ± 0.202	0.365 ± 0.194	0.359 ± 0.193	0.308 ± 0.201
$\mathcal{S}(K^+K^-)$	0.147 ± 0.022	0.199 ± 0.028	0.198 ± 0.028	0.211 ± 0.035
$\mathcal{S}(K^0\bar{K}^0)$	-0.043 ± 0.004	-0.044 ± 0.004	-0.044 ± 0.004	-0.043 ± 0.004

BR in units of 10^{-6}

Lessons Learned From Other Modes

- The following are some major conclusions that will not be reviewed in detail here:
- To explain the *PP* modes involving η or η' (particularly the large BR's of $\eta' K$), one needs to introduce a sizeable singlet-penguin contribution S (with $|S/P_{\mathrm{EW}}| \sim 4$ and about same strong phase) to interfere with P.
- A sizeable singlet-penguin amplitude S_{V} (but not S_{P}) is also required for *VP* modes (particularly for the large BR's of ηK^*).
- Such large singlet-penguin amplitudes are also difficult to accommodate in the perturbative picture.
- The strong phases of P_{P} and P_{V} must differ by about 180° in order to have the right interference pattern in data.

Examination of Flavor Symmetry

Simple Test

- We can examine the flavor SU(3) principle by paying attention to closely related decay modes.
- A simple test of the SU(3) assumption can be done by comparing $|p|$ from $B^0 \to K^0 \underline{K}^0$ and $B^+ \to K^+ K^0$ with $|p'|$ from $B^+ \to K^0 \pi^+$, one gets $|p/p'| = 0.23 \pm 0.02$, consistent with $|V_{cd}/V_{cs}|$.
- This partly justifies our use of $SU(3)_F$ as the working assumption and that f_K / f_π is not preferred when relating p to p'.

The $B_{u,d,s} \to K\pi$ Modes

- Employing *U*-spin symmetry, one has $\left(\tilde{\lambda} \equiv \left|\frac{V_{us}}{V_{ud}}\right| \simeq 0.2317\right)$

$$
\begin{aligned}
A(B^+ \to K^0 \pi^+) &= P \,, \\
A(B^0 \to K^+ \pi^-) &= T\, e^{i(\delta_d + \gamma)} + P \,, \\
\xi A(B_s \to K^- \pi^+) &= \frac{1}{\tilde{\lambda}} T\, e^{i(\delta_s + \gamma)} - \tilde{\lambda} P \,,
\end{aligned}
$$

  where the SU(3)-breaking factor according to factorization

$$
\xi \equiv \frac{f_K F_{B^0\pi}(m_K^2)}{f_\pi F_{B_s K}(m_\pi^2)} \frac{m_{B^0}^2 - m_\pi^2}{m_{B_s}^2 - m_K^2} = 0.97^{+0.09}_{-0.11}
$$

  corresponding to exact symmetry.

- It has been proposed to extract the weak phase γ from these modes if one assumes the same relative strong phase $\delta_d = \delta_s$.

Gronau & Rosner 2000; Chiang & Wolfenstein 2000

Test Flavor Symmetry

Chiang, Gronau & Rosner 2008

- Given the facts that γ has been constrained using other method (*e.g.*, *DK* modes) and that the last mode is not measured until recently by CDF, we turn the argument around to test the flavor symmetry assumption.
- Current data on these modes (BR in units of 10^{-6}):

Observable	Exp. Value	Ref.
$BR(B^+ \to K^0\pi^+)$	23.1 ± 1.0	HFAG
$BR(B^0 \to K^+\pi^-)$	19.4 ± 0.6	HFAG
$A_{CP}(B^0 \to K^+\pi^-)$	-0.097 ± 0.012	HFAG
$BR(B_s \to K^-\pi^+)$	5.27 ± 1.17	CDF
$A_{CP}(B_s \to K^-\pi^+)$	0.39 ± 0.17	CDF

agree with our flavor symmetry predictions of $(5.0\pm1.0)\times10^{-6}$ and 0.28 ± 0.06 (JHEP2006)

Observables

- Consider ratios of the CP-averaged rates and DCPA's:

$$R_d = 1 + r^2 + 2r\cos\gamma\cos\delta_d = 0.899 \pm 0.048 \ ,$$

$$\xi^2 R_s = \tilde{\lambda}^2 + \left(\frac{r}{\tilde{\lambda}}\right)^2 - 2r\cos\gamma\cos\delta_s = 0.260 \pm 0.059 \ ,$$

$$R_d A_{CP}(B^0 \to K^+\pi^-) = 2r\sin\gamma\sin\delta_d = 0.087 \pm 0.012 \ ,$$

$$\xi^2 R_s A_{CP}(B_s \to K^-\pi^+) = -2r\sin\gamma\sin\delta_s = -0.101 \pm 0.050 \ .$$

- The last two equations imply a simple relation between the strong phases

$$\frac{\sin\delta_d}{\sin\delta_s} = -\frac{A_d}{\xi^2 A_s} = -\frac{R_d A_{CP}(B^0 \to K^+\pi^-)}{\xi^2 R_s A_{CP}(B_s \to K^-\pi^+)} = 0.96 \pm 0.54 \ .$$

  meaning that the two should be roughly the same.

- But the B_s branching ratio is inconsistent with this.

Solving All 4 Eqs.

- Left plot always has large SU(3) breaking in δ's.
- Right plot gives reasonable solution for large BR's of B_s.

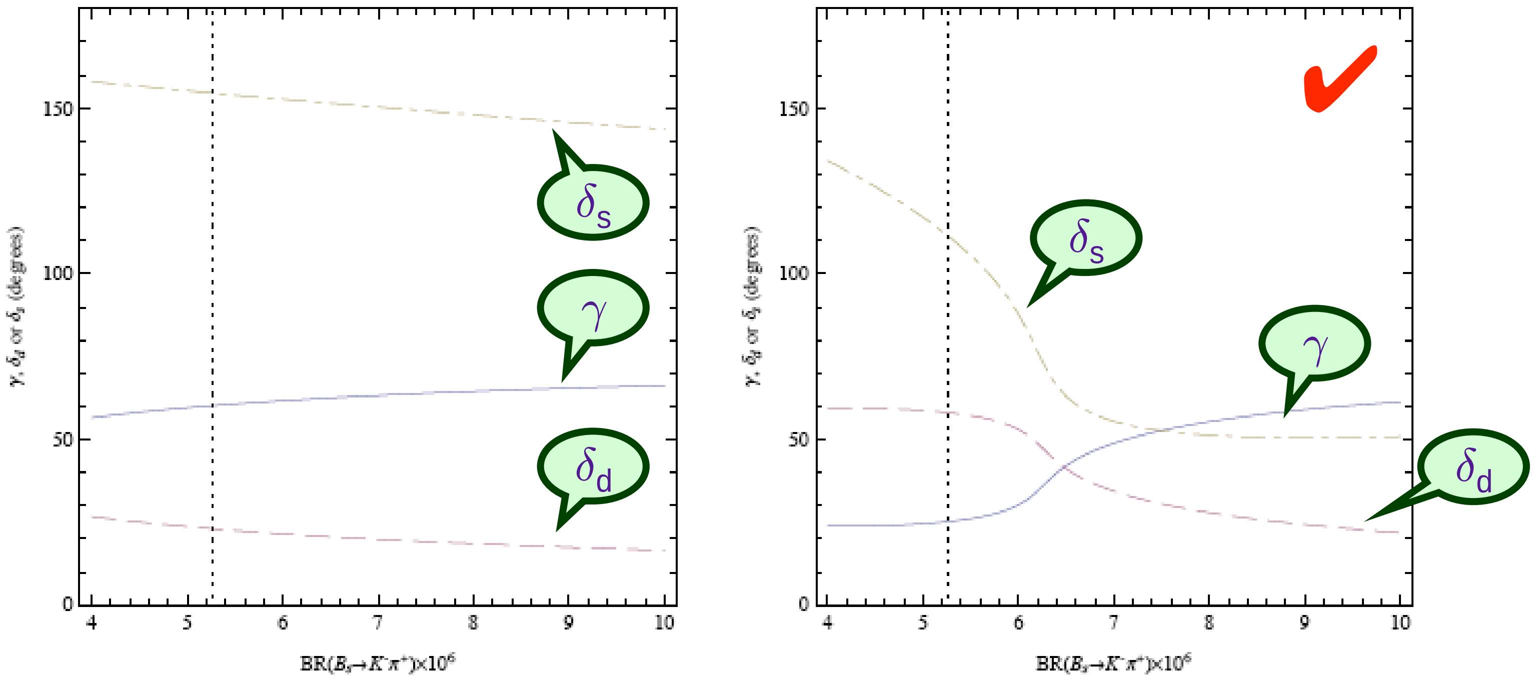


Figure 3: Behavior of solutions as a function of $\mathcal{B}(B_s \to K^-\pi^+)$, assuming $r < 0$. There are two sets of solutions (left and right) when δ_d and δ_s are treated as independent parameters. The solid, dashed and dash-dotted curves represent γ, δ_d and δ_s, respectively. The vertical dotted line indicates the current central value of $\mathcal{B}(B_s \to K^-\pi^+)$.

Possible Solution

- The B_s branching ratio is extracted by CDF using the following relation

$$\frac{f_s}{f_d}\frac{BR(B_s \to K^-\pi^+)}{BR(B^0 \to K^+\pi^-)} = 0.071 \pm 0.010(\text{stat.}) \pm 0.007(\text{sys.}) \ ,$$

with world averages (HFAG): $f_s = (10.4 \pm 1.4)\%$, $f_d = (39.8 \pm 1.0)\%$.

- Solutions with smaller SU(3) breaking, such as those which would result if the BR(B_s) were at least 42% larger than its nominal value, would be suggested if recent evaluations of *b* quark fragmentation had over-estimated the fraction of *b* quarks ending up as B_s.

The $K\pi$ Puzzle

The Old $K\pi$ Puzzle

$$\begin{aligned} A(B^+ \to K^0\pi^+) &= P' \\ \sqrt{2}A(B^+ \to K^+\pi^0) &= -(P' + T' + C' + P'_{EW}) \\ A(B^0 \to K^+\pi^-) &= -(P' + T') \\ \sqrt{2}A(B^0 \to K^0\pi^0) &= P' - C' - P'_{EW} \end{aligned}$$

- Consider the following quantities:

2.4σ (2004) → 1.4σ (2008)

$$R_c \equiv \frac{2\overline{\Gamma}(B^+ \to K^+\pi^0)}{\overline{\Gamma}(B^+ \to K^0\pi^+)} = \left|\frac{p+t+c}{p}\right|^2 = 1.15 \pm 0.12 \to 1.12 \pm 0.07 \;,$$

$$R_n \equiv \frac{1}{2}\frac{\overline{\Gamma}(B^0 \to \pi^-K^+)}{\overline{\Gamma}(B^0 \to \pi^0K^0)} = \left|\frac{p+t}{p-c}\right|^2 = 0.78 \pm 0.10 \to 0.98 \pm 0.07 \;.$$

- The old puzzle is disappearing. However, it is claimed that there is a more serious new puzzle because it occurs in the CP asymmetries...

The New $K\pi$ Puzzle

- The $K^+\pi^0$ and $K^+\pi^-$ modes have quite different DCPA's:

$$\Delta A = A_{CP}(K^+\pi^0) - A_{CP}(K^+\pi^-) = 0.147 \pm 0.028$$

>5σ !

- The difference is normally expected to be small in the SM. However, this is not true if C or P_{EW} are sizeable.
- This leads to two possible explanations:

(1) Sizeable C with large strong phase relative to T, as found in the flavor SU(3) framework [this is also partly favored by the large BR($\pi^0\pi^0$)]; or

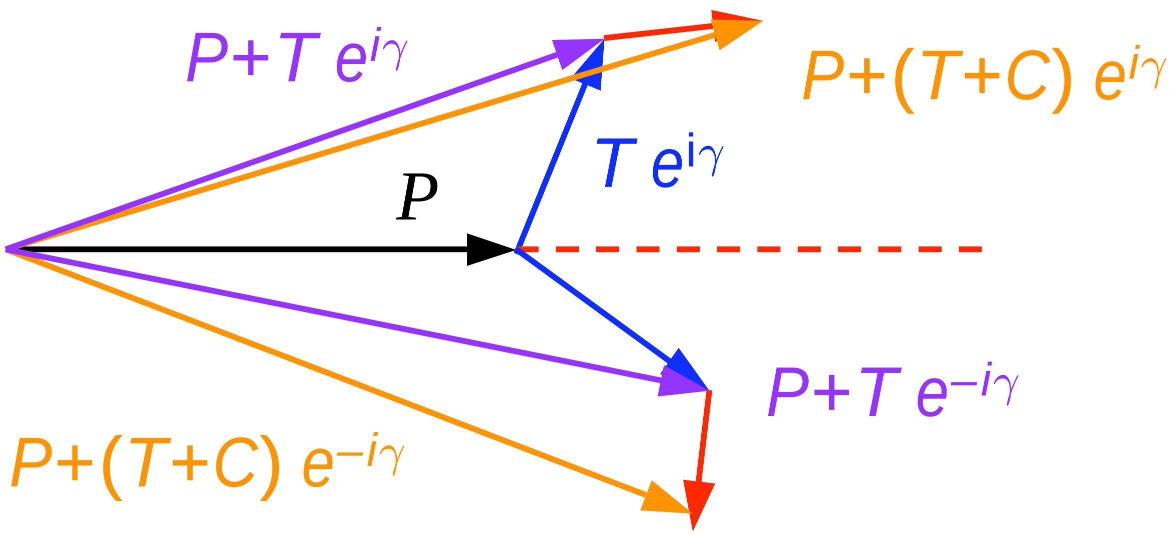
Chiang et. al. 2004
Li, Mishima & Sanda 2005

(2) Sizeable new physics contribution with a new weak phase entering through the EWP loop.

Yoshikawa 2003; Mishima & Yoshikawa 2004;
Buras et. al. 2004, 2006; Baek & London 2007;
Hou et. al. 2007; Feldmann, Jung & Mannel 2008

Large Color-Suppress Amplitude

- From global fits, we observe a large C, with the ratio $|C/T| = 0.63 \pm 0.08$ and a sizeable relative strong phase of $(-56 \pm 10)^\circ$ between them.
- The relative strong phase between T and P is $(19 \pm 3)^\circ$.
- Pictorially,



New Physics Interpretation

Chiang & Zhou 2006

- Add one new amplitude to *c*′ (EWP-like)

$$c' \to Y_{sb}^{u}\xi_c C - (Y_{sb}^{u} + Y_{sb}^{c})\, P_{EW} + N \ .$$
$$\text{with } N = |N| \exp\left[i(\phi_N + \delta_N)\right]$$

- The value of $\chi^2_{\rm min}$ reduces from ~ 16 to ~4.
- We obtain |*N*|~18 eV (1/3 of the QCD-penguin amplitude), ϕ_N ~ 90°, and δ_N ~ –15°.

- Conclusion: The new *K* π puzzle poses challenges for theorists to understand better the strong dynamics (whether *C* is indeed large and possesses a sizeable strong phase relative to *T*) as well as to explore new physics possibilities.

Extraction of γ from Charmless Modes

Using Charmed Modes

Gronau & Wyler 1991
Gronau & London 1991
Atwood et. al. 1997

- Methods have been proposed to determine γ using the DCPA resulted from interference between different amplitudes in $B \to D^{(*)}K$ decays.
- Such early proposals are not completely free from hadronic uncertainties.
- Recently, a Dalitz plot analysis is used to simultaneously determine γ and other hadronic parameters.
  - BaBar obtains $\gamma = (92 \pm 41 \pm 11 \pm 12)^\circ$ (from DK^- & D^*K^-);
  - Belle obtains $\gamma = (53^{+15}_{-18} \pm 3 \pm 9)^\circ$ (from DK^-, D^*K^- & DK^{*-}).

Giri et. al. 2003; Belle 2004

Using the $K\,\pi$ Modes

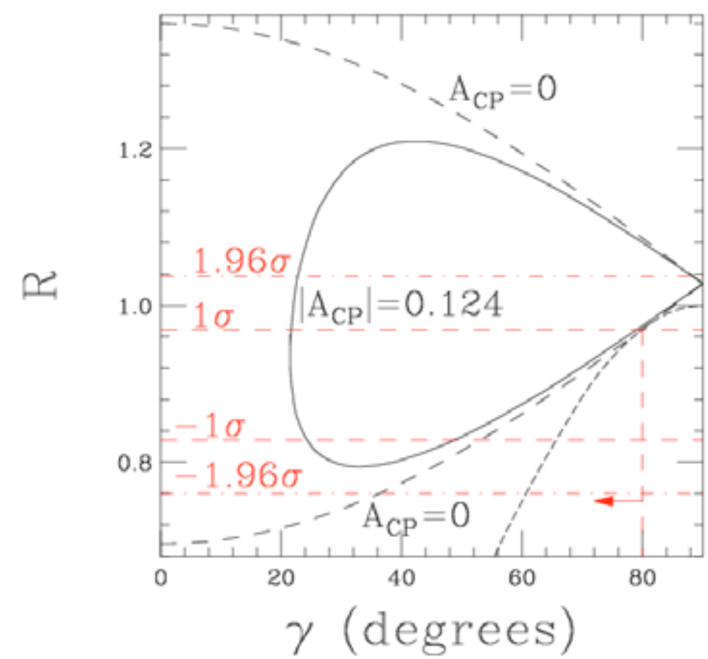
- Rates and asymmetry of some $K\,\pi$ modes can be used to extract the weak phase γ:

$$R \equiv \frac{\overline{\Gamma}(B^0 \to K^+\pi^-)}{\overline{\Gamma}(B^+ \to K^0\pi^+)} = 1 - 2r\cos\gamma\cos\delta + r^2 = 0.816 \pm 0.058\ ,$$

$$A_{CP}^{K^+\pi^-} = -2r\sin\gamma\sin\delta/R = -0.109 \pm 0.019\ .$$

Gronau & Rosner 2003

- Use $r = |T'/P'| = 0.166$ [with $|T'|$ from $B \to \pi\, l\, \nu$ decay by $SU(3)_F$], and obtain $\gamma \leq 80^\circ$ at 1σ level.



The $K^*\pi$ and ρK Modes

Chiang 2005

- With accumulating data it is now possible to consider an alternative method, which employs the $K^*\pi$ and $\rho\, K$ decays to constrain γ.
- A distinction between the $V\, P$ system and the $P\, P$ system is that there are *two types of amplitudes for each topology* in the former case, depending upon whether the spectator quark in B ends up in the P or V meson in the final state.
- The flavor amplitude decomposition and data are given by:

	Mode	Amplitudes	BR $(\times 10^{-6})$	A_{CP}
$B^+ \to$	$K^{*0}\pi^+$	P'_P	10.7 ± 0.8	-0.085 ± 0.057
	$\rho^+ K^0$	P'_V	8.0 ± 1.5	0.12 ± 0.17
$B^0 \to$	$K^{*+}\pi^-$	$-(P'_P + T'_P)$	9.8 ± 1.1	-0.05 ± 0.14
	$\rho^- K^+$	$-(P'_V + T'_V)$	15.3 ± 3.6	0.22 ± 0.23

Some Details

- With $r_1 \equiv |T'_{\mathrm{P}} / P'_{\mathrm{P}}|$, we have:

$$\begin{aligned} A(K^{*+}\pi^-) &= -P'_P\left[1 - r_1 e^{i(\delta_P+\gamma)}\right] \ , \\ R(K^*\pi) &\equiv \frac{\overline{\Gamma}(K^{*+}\pi^-)}{\overline{\Gamma}(K^{*0}\pi^+)} = 1 - 2r_1 \cos\delta_P \cos\gamma + r_1^2 = 0.99 \pm 0.13 \ , \\ \mathcal{A}_{CP}^{K^{*+}\pi^-} &= -2r_1 \sin\delta_P \sin\gamma / R(K^{*+}\pi^-) = -0.05 \pm 0.14 \ . \end{aligned}$$

- With $r_2 \equiv |T'_{\mathrm{V}} / P'_{\mathrm{V}}|$, we have:

$$\begin{aligned} A(\rho^- K^+) &= P'_V\left[1 + r_2 e^{i(\delta_V+\gamma)}\right] \ , \\ R(\rho^- K^+) &\equiv \frac{\overline{\Gamma}(\rho^- K^+)}{\overline{\Gamma}(\rho^+ K^0)} = 1 + 2r_2 \cos\delta_V \cos\gamma + r_2^2 = 2.06 \pm 0.61 \ , \\ \mathcal{A}_{CP}^{\rho^- K^+} &= 2r_2 \sin\delta_V \sin\gamma / R(\rho^- K^+) = 0.22 \pm 0.23 \ . \end{aligned}$$

- There are 4 observables in terms of 5 parameters.

Value of γ

- Instead of treating r_1 and r_2 independently, one may employ the factorization assumption and get (depending upon form factor models)

$$\frac{r_2}{r_1} = \frac{|T'_V|}{|T'_P|}\frac{|P'_P|}{|P'_V|} = \frac{f_K A_0^{B\rho}(m_K^2)}{f_{K^*} F_1^{B\pi}(m_{K^*}^2)} \left|\frac{P'_P}{P'_V}\right| \simeq 0.6 \sim 1.1$$

- This number can be compared with the result of 0.7 ± 0.1 obtained from a global fit.

Chiang et. al. 2004

- There are now four parameters for the four observables in the above-mentioned equations.
- Solving them exactly becomes possible and gives

  $\gamma = (65^{+10}_{-8})^\circ$ for $r_2/r_1 = 0.6$; and

  $\gamma = (68^{+9}_{-7})^\circ$ for $r_2/r_1 = 1.1$.

Summary

- Global fitting to current rare *PP* and *VP* decays of the B mesons within the framework of flavor symmetry is generally good.
- The new $K\pi$ problem can be accommodated with either (1) a large *C* with a sizeable strong phase relative to *T*, or (2) a sizeable new physics amplitude with nontrivial strong and weak phases.
- If the large *C* explanation is taken, then the strong dynamics needs to be better understood. The same comment applies to the singlet-penguin amplitude as well.

Summary

- Examination of the $B_{u,d,s} \to K\pi$ modes indicates that the flavor symmetry is respected only if BR($B_s \to K^- \pi^+$) is at least 42% larger or, equivalently, the SU(3)-breaking factor is bigger than 1.2.
- It is possible to constrain the weak phase γ using the BR's and CPA's of a set of $K^* \pi$ and ρK modes with only a mild assumption of factorization for the tree amplitudes.

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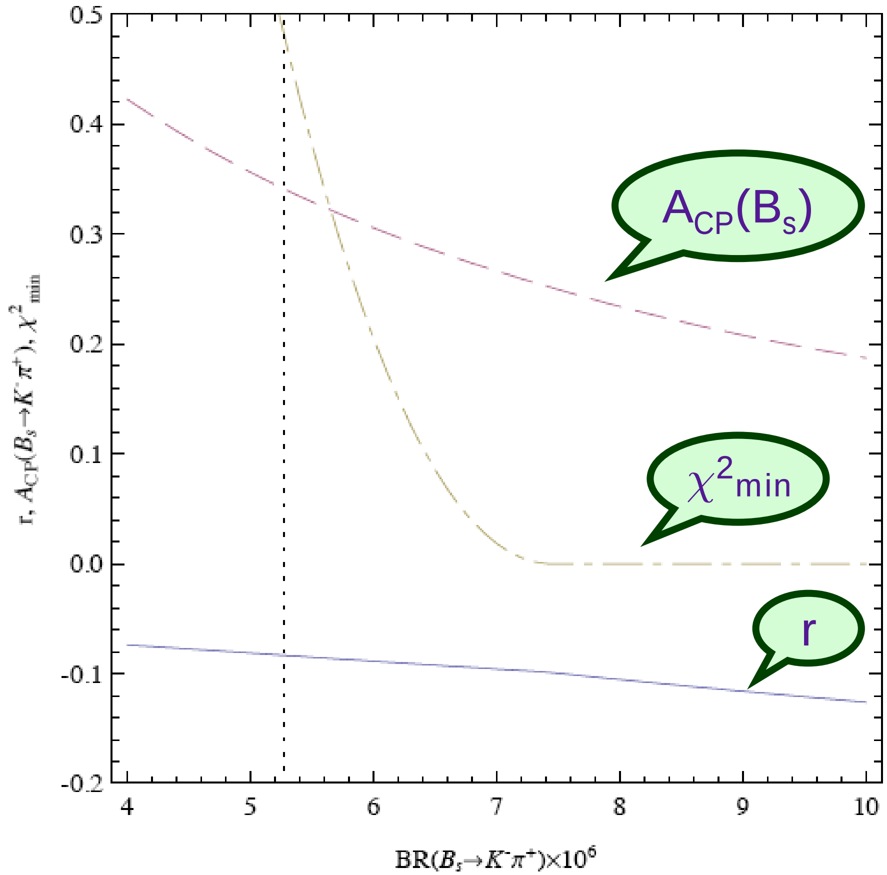
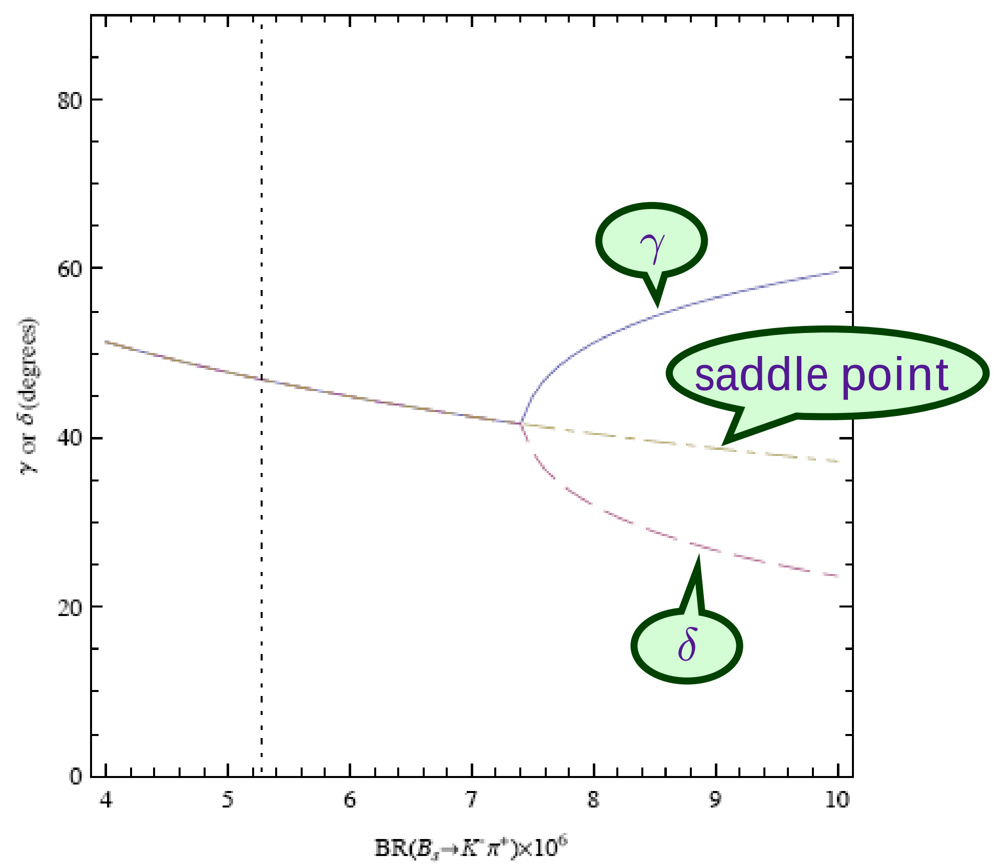
SU(3) Global Fits to Rare Decays

- Advantages:
  (1) it is less sensitive to statistical fluctuations of individual observables (particularly for rare processes);
  (2) it helps finding out which observable deviates from theory and how serious that is (leading to new physics); and
  (3) it tests the flavor symmetry assumption by making predictions for unseen modes.

Fitting First 3 Eqs. With $\delta_d = \delta_s \equiv \delta$

- Behavior of solutions as functions of BR($B_s \to K^- \pi^+$), assuming r<0 and same strong phase.
- No perfect solution for BR($B_s \to K^- \pi^+$)<7.5×10^{-6}.





SU(3) Breaking

- Suppose *T* and *P* are allowed to scale independently and differently from the factorization prediction.
- Use $\gamma = (67.6 \pm 4.5)^\circ$ obtained from other methods as well.
- No perfect solution for $\delta_s - \delta_d < 20^\circ$
- When $\delta_s - \delta_d > 20^\circ$, (r, γ, δ_d) become fixed at $(-0.182, 67.6^\circ, 15^\circ)$.