Flavor SU(3) analysis of charmless $B \to PP$ Decays

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In collaboration with

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C.W. Chiang and YFZ, JHEP0621,027(2006)

Outline

- √ Overview: the unitarity triangle(UT)and $B \to PP$ decays .
- √ Trends in the latest data and "puzzles".
- √ Determining UT from $B \to PP$ only.
  - ⋆ The flavor $SU(3)$ topology
  - ⋆ inputs and scenarios.
  - ⋆ Global fitting results and implications
- √ Predicting for $B_s \to PP$ modes
- √ Summary

The CKM Matrix

In SM, the CKM matrix is the only source of weak CP violation

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

Hierarchy in CKM matrix controlled by $\lambda \simeq 0.23$.

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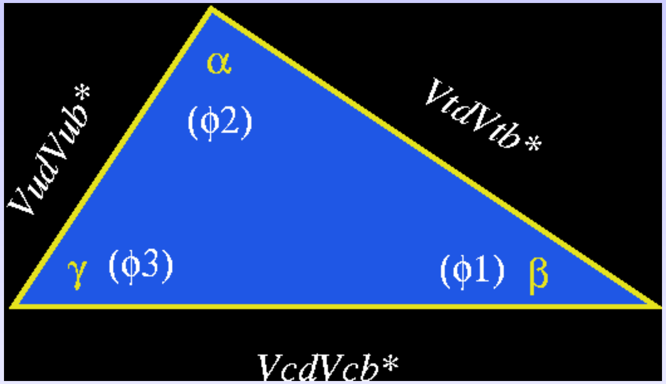

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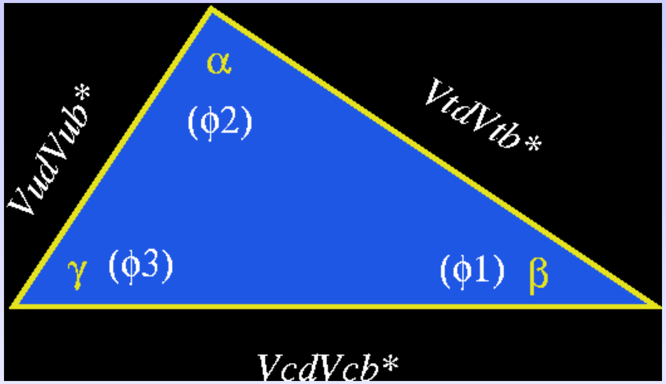

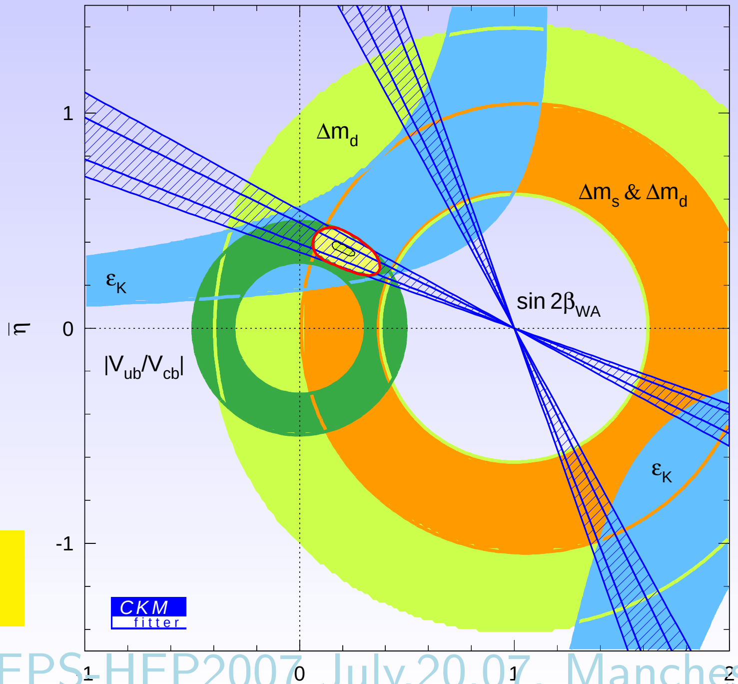

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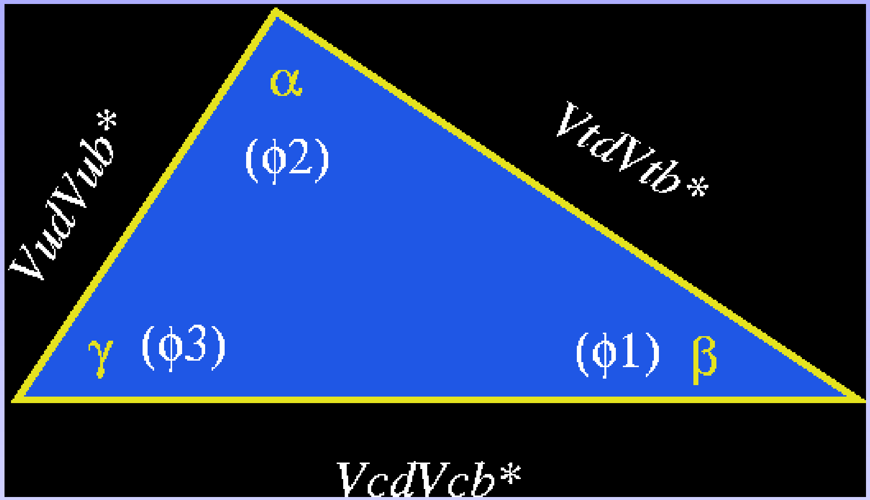
UT and hadronic charmless B decays

Big effects of CP violation in B meson system



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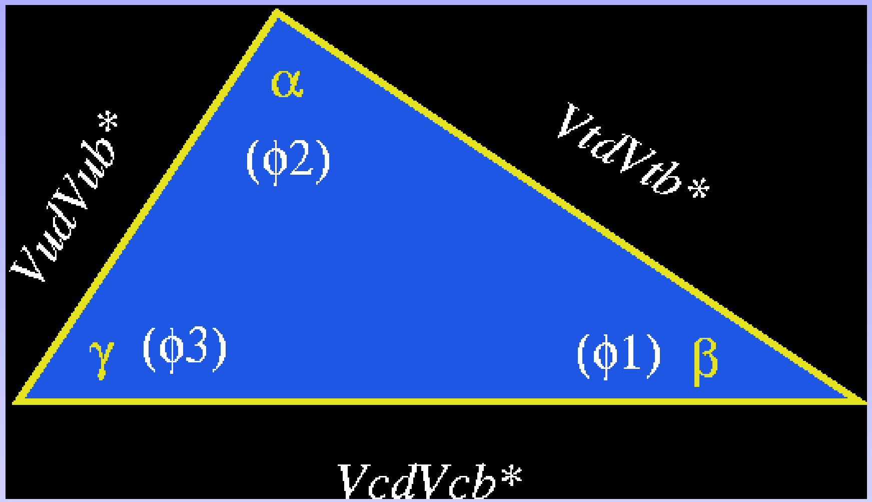

- ✓ $\alpha(\phi_2)$: $B \to \pi\pi, \rho\pi$ (mixing-induced CPV)
- ✓ $\beta(\phi_1)$: $B \to \pi^0 K_S, \eta^{(\prime)} K_S$ (mixing-induce CPV)

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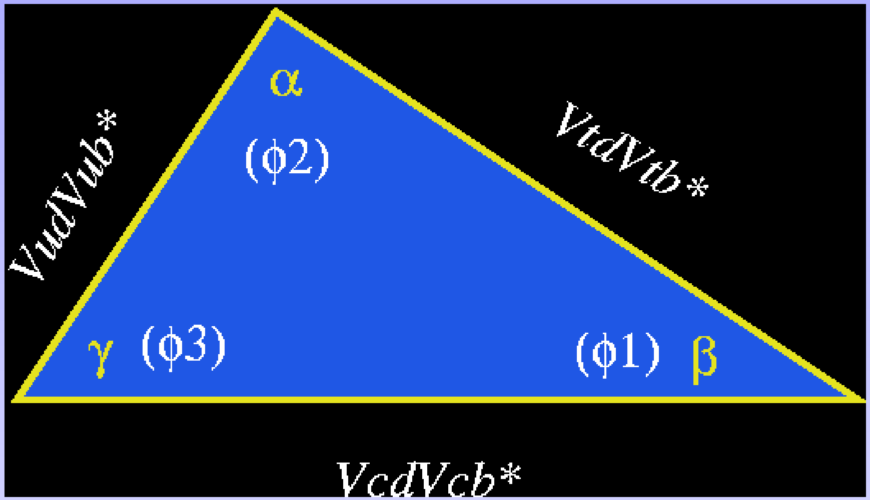


- √ $\alpha(\phi_2)$: $B \to \pi\pi, \rho\pi$ (mixing-induced CPV)
- √ $\beta(\phi_1)$: $B \to \pi^0 K_S, \eta^{(\prime)} K_S$ (mixing-induce CPV)
- √ $\gamma(\phi_3)$: $B \to \pi K, 3\pi,$ (direct CPV)

CP violations in B decays

- ✓ Mixing induced CP violation

$$S = \frac{\Gamma_{\bar{B}\to f_{cp}}(t) - \Gamma_{B\to f_{cp}}(t)}{\Gamma_{\bar{B}\to f_{cp}}(t) + \Gamma_{B\to f_{cp}}(t)} \sim Im(e^{-2i\beta}\frac{\bar{A}}{A})$$

Eg.

- ⋆ $B \to J/\psi K_S$: S$=\sin 2\beta = 0.687 \pm 0.032$.
- ⋆ $B \to \phi K_S$: $S \simeq \sin 2\beta = 0.39 \pm 0.18$

- ✓ Direct CP violation (need strong phase)

$$a_{CP} = \frac{\Gamma_{\bar{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\bar{B}\to\bar{f}} + \Gamma_{B\to f}} \sim \sin\gamma\sin\delta$$

$B \to \pi\pi, \pi K, \pi\eta(\eta'), K\eta(\eta')$ etc. Important to independently determine α, β and γ.

Effective Hamiltonian for B decays

Effective Hamiltonian

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[V_{ub} V_{uq}^* \left(C_1 O_1^u + C_2 O_2^u \right) - V_{tb} V_{tq}^* \left(\sum_{i=3}^{10} C_i \, O_i + C_g O_g \right) \right.$$

Theoretical calculations for matrix elements

- ✓ QCD factorization — Beneke, Buchala, Neubert, Sachrajda

  Strong phases from Penguin contractions and hard gluon exchange. Λ/m_B corrections hard to estimate.

- ✓ Perturbative QCD — Li, Kuem and Sanda

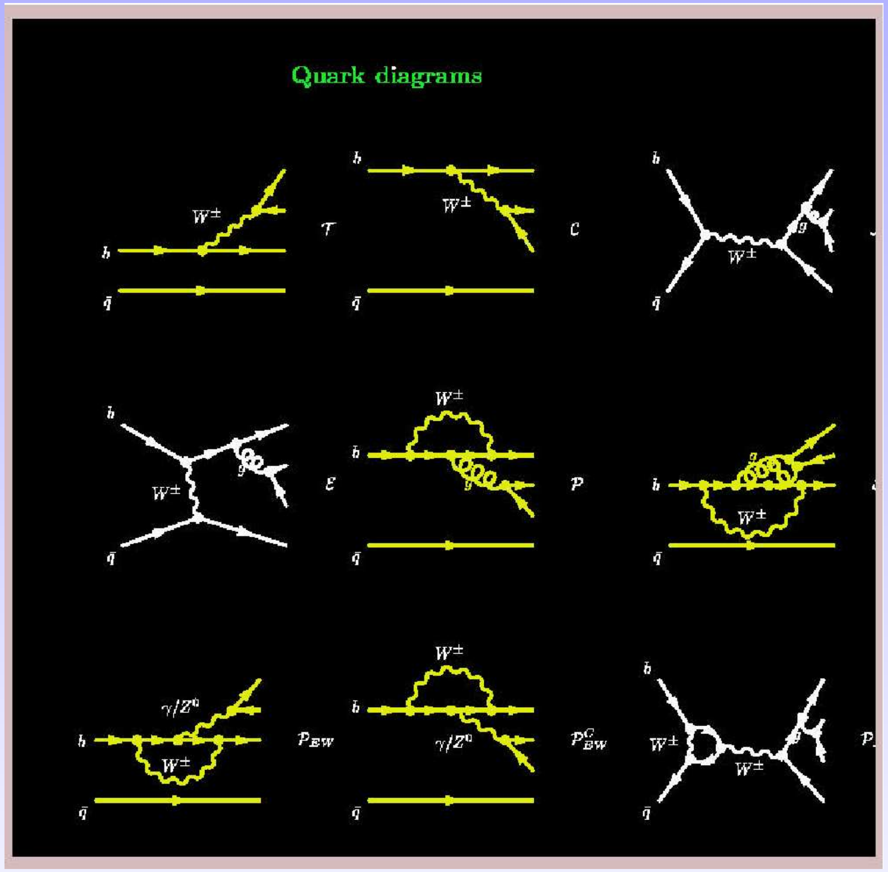
  Strong phases from annihilation diagrams

- ✓ Soft collinear effective theory — Baur, Pirjol, Stewart

  Charming penguins important.

flavor flow topology within SU(3)

Quark flavor flow diagrams: Chau 84,91, Savage, Wise, 89, Gronau 95



$\mathcal{T}$: tree

$\mathcal{C}$: color-suppressed

$\mathcal{P}$: QCD penguin

$\mathcal{S}$: singlet penguin

$\mathcal{P}_{EW}$: EW penguin

$\mathcal{P}_{EW}^{C}$: color-suppressed

$\mathcal{A}$: Annihilation

$\mathcal{E}$: Exchange

$\mathcal{P}_{A}$: P-annihilation

NOT Feynman diagrams

Diagrammatic decomposition

$B \to \pi\pi$ and πK amplitudes

$$\begin{aligned}
\bar{A}(\pi^+\pi^-) &= -(\mathcal{T}+\mathcal{E}+\mathcal{P}+\mathcal{P}_A+\frac{2}{3}\mathcal{P}_{EW}^C) \\
\bar{A}(\pi^0\pi^0) &= -\frac{1}{\sqrt{2}}(\mathcal{C}-\mathcal{E}-\mathcal{P}-\mathcal{P}_A+\mathcal{P}_{EW}+\frac{1}{3}\mathcal{P}_{EW}^C) \\
\bar{A}(\pi^0\pi^-) &= -\frac{1}{\sqrt{2}}(\mathcal{T}+\mathcal{C}+\mathcal{P}_{EW}+\mathcal{P}_{EW}^C) \\
\bar{A}(\pi^+K^-) &= -(\mathcal{T}'+\mathcal{P}'+\frac{2}{3}\mathcal{P}_{EW}'^C) \\
\bar{A}(\pi^0\overline{K}^0) &= -\frac{1}{\sqrt{2}}(\mathcal{C}'-\mathcal{P}'+\mathcal{P}_{EW}'+\frac{1}{3}\mathcal{P}_{EW}'^C) \\
\bar{A}(\pi^-\overline{K}^0) &= \mathcal{A}'+\mathcal{P}'-\frac{1}{3}\mathcal{P}_{EW}'^C \\
\bar{A}(\pi^0K^-) &= -\frac{1}{\sqrt{2}}(\mathcal{T}'+\mathcal{C}'+\mathcal{A}'+\mathcal{P}'+\mathcal{P}_{EW}'+\frac{2}{3}\mathcal{P}_{EW}'^C)
\end{aligned}$$

$B \to \eta^{(\prime)}K$ amplitudes ($\mathcal{S}$ involved, $\theta = \sin^{-1}(1/3) \simeq 19.5^\circ$)

$$\bar{A}(\bar{K}^0\eta') = \frac{1}{\sqrt{6}}(\mathcal{C}'+3\mathcal{P}'+4\mathcal{S}'-\frac{1}{3}\mathcal{P}_{EW}'-\frac{1}{3}\mathcal{P}_{EW}^{c'})$$

factorize out CKM elements

Define $\lambda_u^{(s)} = V_{ub}V^*_{ud(s)}, \lambda_c^{(s)} = V_{cb}V^*_{cd(s)}$

$$\bar{A}_{\pi^+\pi^-} = \lambda_u(T - P_{tu} - \frac{2}{3}P^C_{EW,tu}) - \lambda_c(P + \frac{2}{3}P^C_{EW})$$

$$\bar{A}_{\pi^-\pi^0} = -\frac{1}{\sqrt{2}}\left[\lambda_u(T + C - \hat{P}_{EW,tu}) - \lambda_c\hat{P}_{EW}\right]$$

$$\bar{A}_{\pi^0\pi^0} = \frac{1}{\sqrt{2}}\left[\lambda_u(-C - P_{tu} + \hat{P}_{EW,tu} - \frac{2}{3}P^C_{EW,tu}) - \lambda_c(P - \hat{P}_{EW} + \frac{2}{3}P^C_{EW})\right]$$

$$\bar{A}_{\pi^+K^-} = \lambda_u^s(T' - P'_{tu} - \frac{2}{3}P'^C_{EW,tu}) - \lambda_c^s(P' + \frac{2}{3}P'^C_{EW})$$

$$\bar{A}_{\pi^0\bar{K}^0} = \frac{1}{\sqrt{2}}\left[\lambda_u^s(-C' - P'_{tu} + \hat{P}'_{EW,tu} - \frac{2}{3}P^C_{EW,tu}) - \lambda_c^s(P' - \hat{P}'_{EW} + \frac{2}{3}P^C_{EW})\right]$$

$$\bar{A}_{\pi^-\bar{K}^0} = \lambda_u^s(P'_{tu} - \frac{1}{3}P'^C_{EW,tu}) + \lambda_c^s(P' - \frac{1}{3}P'^C_{EW})$$

$$\bar{A}_{\pi^0K^-} = -\frac{1}{\sqrt{2}}\left[\lambda_u^s(T' + C' - P'_{tu} - \hat{P}'_{EW,tu} + \frac{1}{3}P'^C_{EW}) - \lambda_c^s(P' + \hat{P}'_{EW} - \frac{1}{3}P'^C_{EW})\right]$$

SU(3) Limit: $T = T'$, $P = P'$, $\ldots$

SU(3) breaking brings back model-dependence

Relative sizes of diagrams

Estimate from naive(QCD) factorization:
$(2 < N_c < \infty)$

$T \simeq a_1 \cdot k$	$0.9 \sim 1.1$	0.91
$C \simeq a_2 \cdot k$	$-0.33 \sim 0.25$	$0.18 - 0.08i$
$P \simeq (a_4 + a_6 R) \cdot k$	0.09	$0.085 + 0.011i$
$P_{EW} \simeq -\frac{3}{2}(a_7 - a_9) \cdot k$	$0.013 \sim 0.015$	0.0013
$P_{EW}^C \simeq -\frac{3}{2}(a_8 R + a_{10}) \cdot k$	$-0.0023 \sim 0.003$	$0.0017 - 0.0008i$

with $R = m_\pi^2/(m_b - \hat{m})\hat{m}$ and $k \simeq 0.92$. Typical size

$$\frac{C}{T} \leq 0.2, \quad \frac{P}{T} \simeq 0.09, \quad \frac{P_{EW}}{P} \simeq 0.15$$

The data (WA)

	$Br(\times 10^{-6})$	theo.	a_{CP}	S
$\pi^+\pi^-$	5.25 ± 0.24	~ 10.0	0.27 ± 0.07	-0.58 ± 0.09
$\pi^0\pi^0$	1.31 ± 0.21	~ 0.12	-0.15 ± 0.32	
$\pi^0\pi^-$	5.7 ± 0.4	~ 5.4	0.05 ± 0.05	
π^+K^-	19.7 ± 0.6	~ 15	-0.09 ± 0.01	
$\pi^0\bar{K}^0(K_S)$	9.96 ± 0.62	~ 5.7	0.064 ± 0.11	(0.33 ± 0.21)
$\pi^-\bar{K}^0$	$21.9 \pm 1.$	~ 16	0.01 ± 0.02	
π^0K^-	12.8 ± 0.6	~ 10	0.05 ± 0.03	
$K^0\eta'$	64.9 ± 4.4	~ 20	-0.09 ± 0.06	0.60 ± 0.08

Trends of the data and “puzzles”

$\pi\pi$ modes (tree dominant) Fleischer, 07

✓ large $2Br(\pi^0\pi^0)/Br(\pi^+\pi^-) = 0.50 \pm 0.08$

$\Longrightarrow$ require $C/T = 0.6 \sim 0.7$

πK modes (QCD penguin dominant)

✓ Large $A_{cp}(\pi^+K^-) = -0.098 \pm 0.015$ but tiny $A_{cp}(\pi^0K^-) = 0.05 \pm 0.03$ with opposite sign.

$\Longrightarrow$ require $C'/T' = 1 \sim 1.2$

✓ Small $S(\pi^0K_S) = 0.33 \pm 0.21$ compared with $S(J/\psi K_S) = 0.675 \pm 0.026$ $\Longrightarrow$ need new physics?

$K\eta'$ modes (QCD penguin dominant)

✓ Huge $Br(\eta' K^-(K^0)) = 69.7(64.9) \times 10^{-6}$

$\Longrightarrow$ require $S/P \sim 0.4$

Global analysis for charmless $B \to PP$

Motivations:

- ✓ The data is now precise enough for an independent determination of UT from $B \to PP$ only. New physics (if exists) may shown up from a UT with different size and shape.
- ✓ The extracted hadronic amplitudes are valuable for understanding QCD dynamics and making predictions for yet to be seen modes

Inputs Known CKM matrix elements, $|V_{us}|$, $|V_{ub}|$ and $|V_{cb}|$. All charmless $B \to PP$ modes: $\pi\pi$, πK, ($\eta^{(\prime)} K, \pi, \eta^{(\prime)}$ ...).

Parameters T, C, P, (S), P_{EW} with strong phases and $\gamma(\phi_3)$.

Scenarios

- ⋆ SU(3) symmetry with three SU(3) breaking schemes.
- ⋆ Ignoring subleading diagrams P^C_{EW}, E, A.
- ⋆ Including NP effects in electroweak penguin sector, for πK modes and all $\Delta S = 1$ modes.

Fit results: SM case ($\pi\pi + \pi K$)

The global fit is worsen with updated data, mainly due to $S(\pi^0 K_S)$.

Beak, London 07

Goodness of fit: $\chi^2/dof = 16.4/12$

Chiang and YFZ06

Best fitted amplitudes

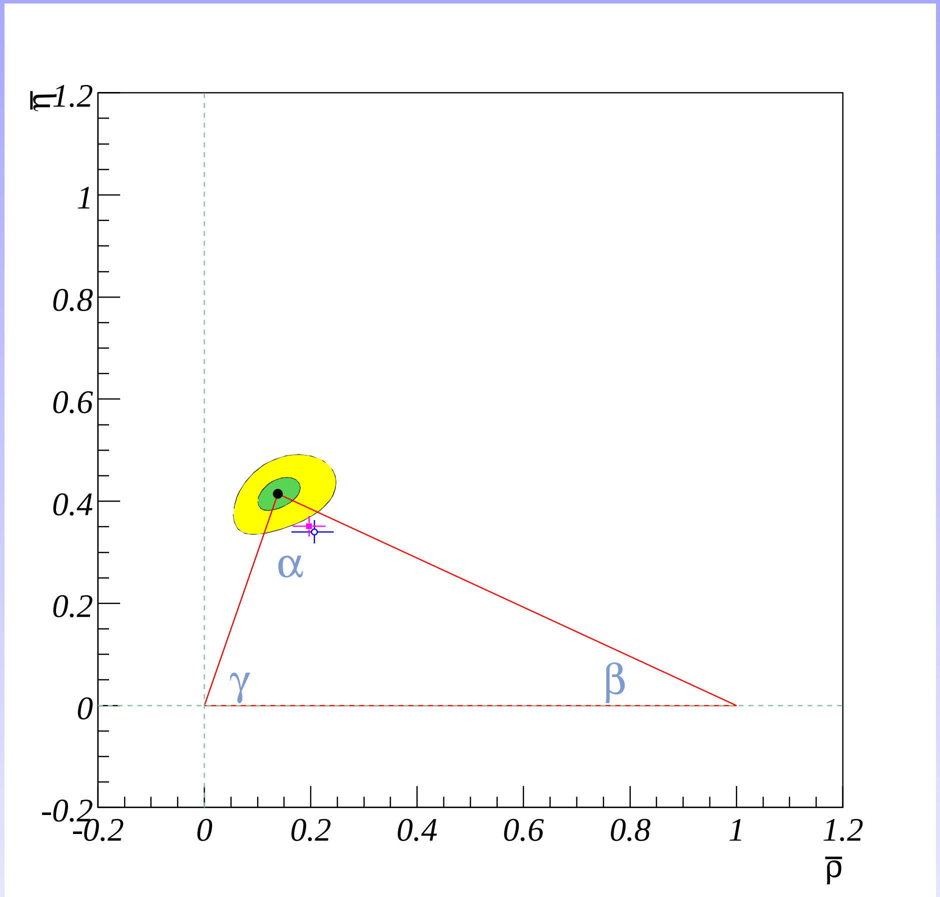
$$T = 0.571^{+0.045}_{-0.040} \qquad C = 0.360 \pm 0.046 \qquad \delta_C = -49.3 \pm 9.1$$

$$P = 0.122 \pm 0.002 \quad \delta_P = -17.6 \pm 2.7 \qquad P_{EW} = 0.011 \pm 0.001$$

$$\delta_{P_{EW}} = -18.7 \pm 4.0$$

- √ Large $C/T = 0.63$ required by both $\pi^0\pi^0$ and πK.
- √ Significant phase difference $-49.3°$ between C and T
- √ The factorization model based SU(3) breaking scheme agree with the data best: $T'/T = f_K/f_\pi$ and $P' = P$

best fitted UT ($\pi\pi + \pi K$)



Best fits:

$\rho = 0.143 \pm 0.033$

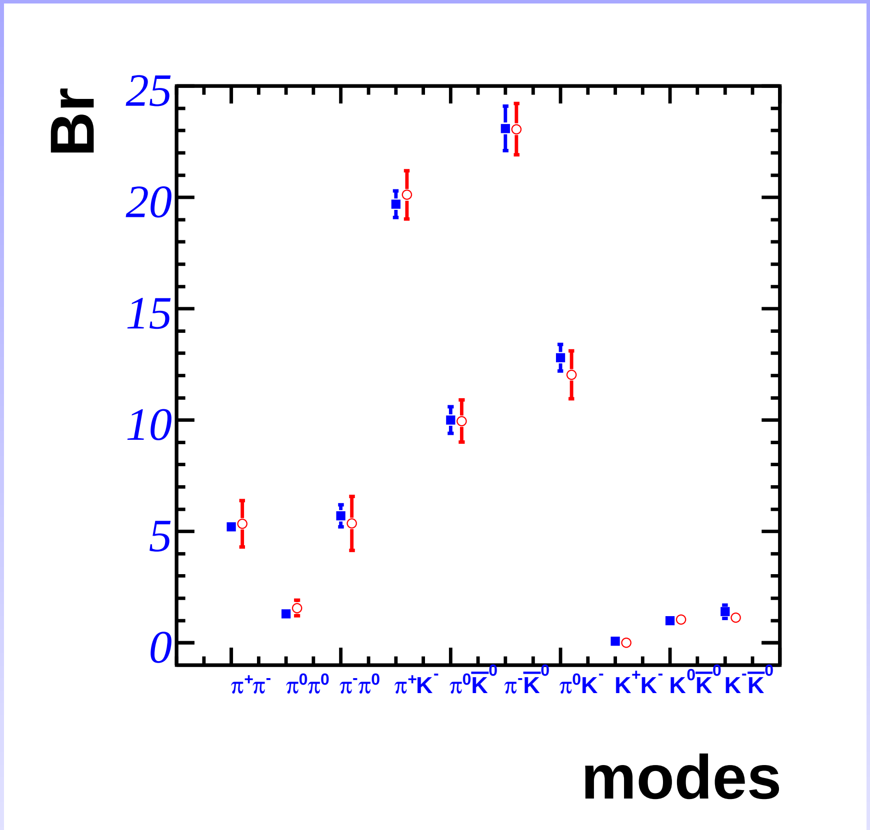
$\eta = 0.418 \pm 0.029$

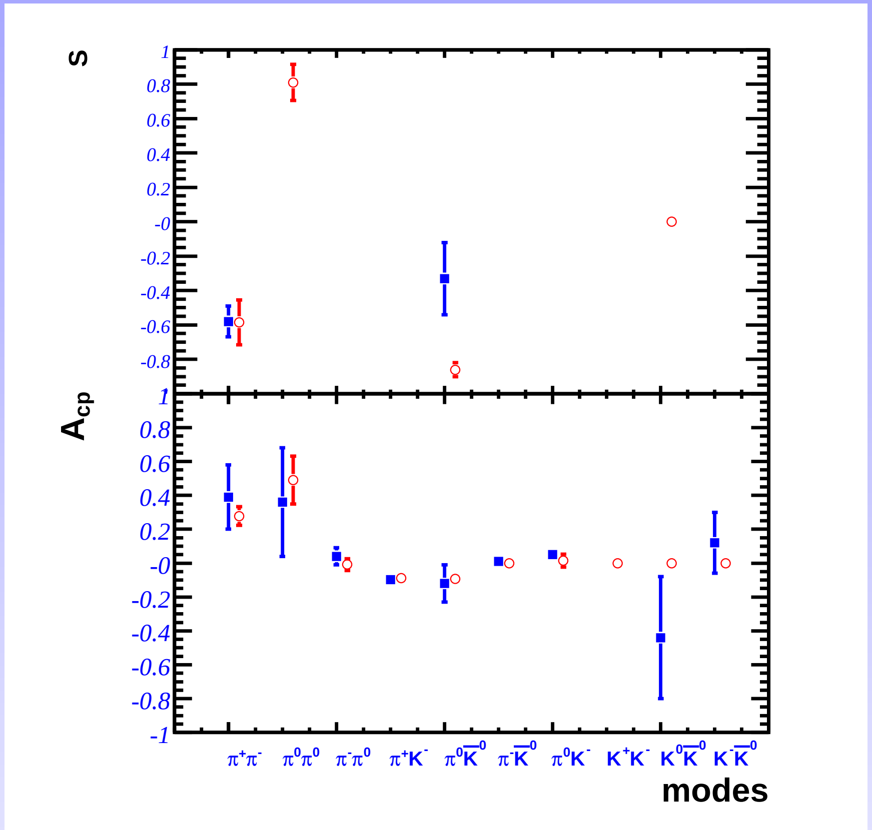
$A = 0.807 \pm 0.012$

phase angles

- √ larger $\gamma = (72 \pm 5)^\circ$
- √ larger $\beta = (26 \pm 2)^\circ$
- √ smaller $\alpha = (83 \pm 7)^\circ$
- √ larger size of UT

best fitted quantities



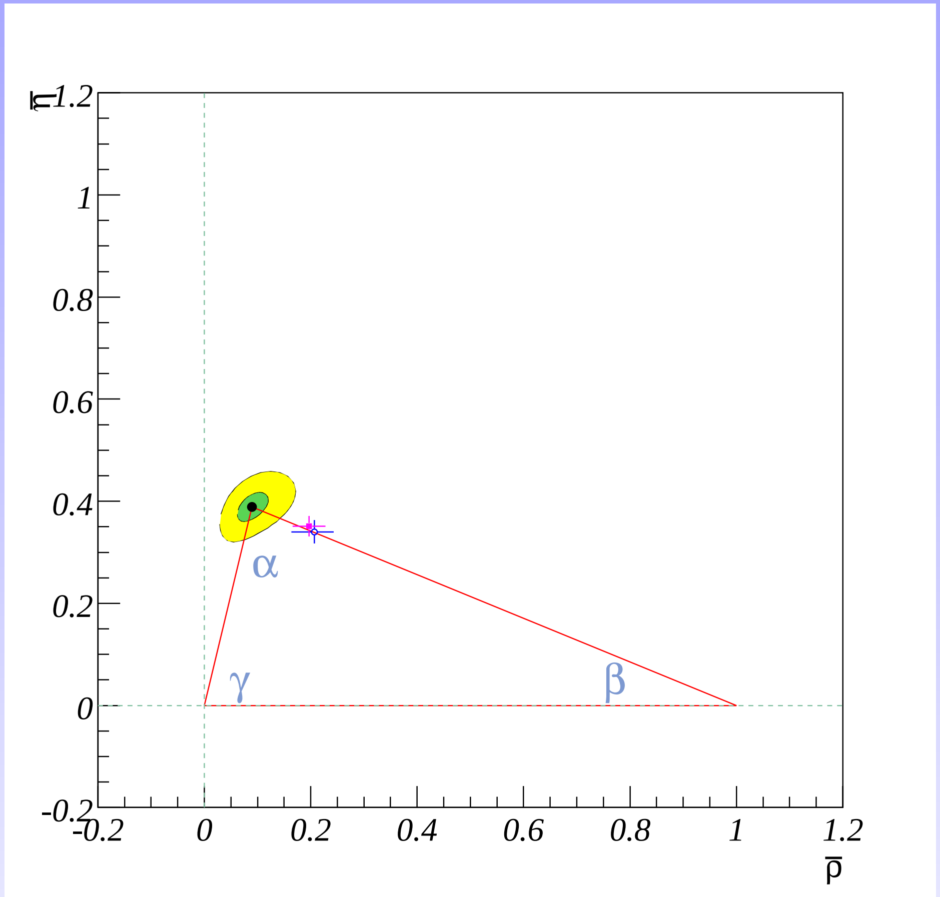


Overall agreement OK.

Fit favors slightly larger $\pi^0\pi^0$, larger π^+K^- and smaller π^0K^-

$S(\pi^0K_S)$ can NOT be reproduced.

best fitted UT with $P\eta^{(\prime)}$



Best fits:

$\rho = 0.087 \pm 0.029$

$\eta = 0.379 \pm 0.027$

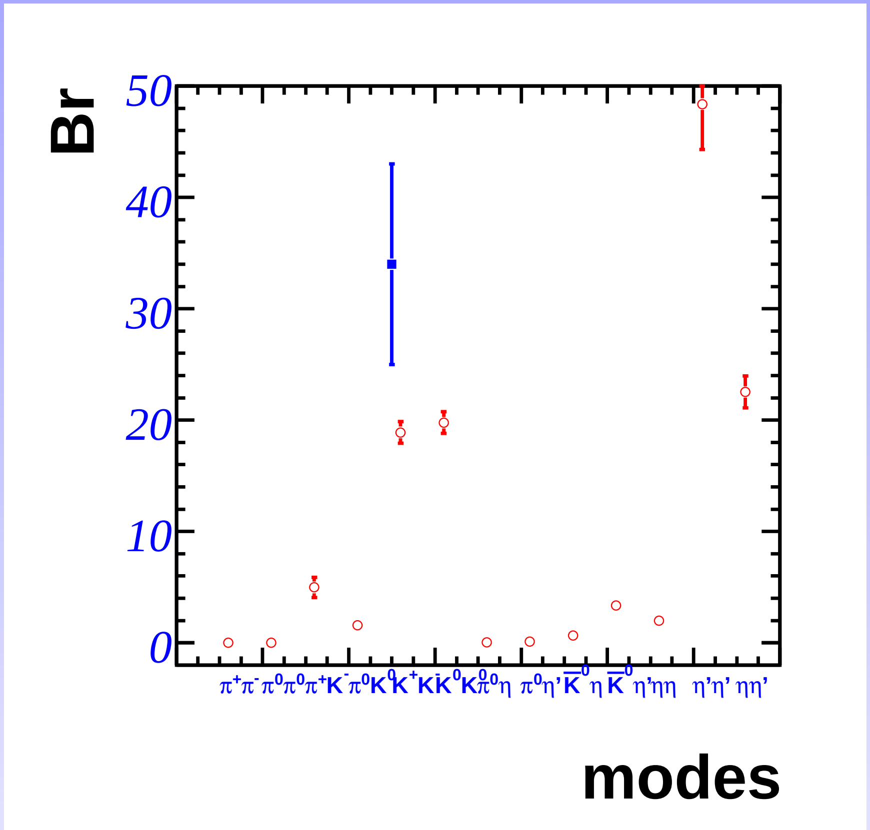
$A = 0.809 \pm 0.012$

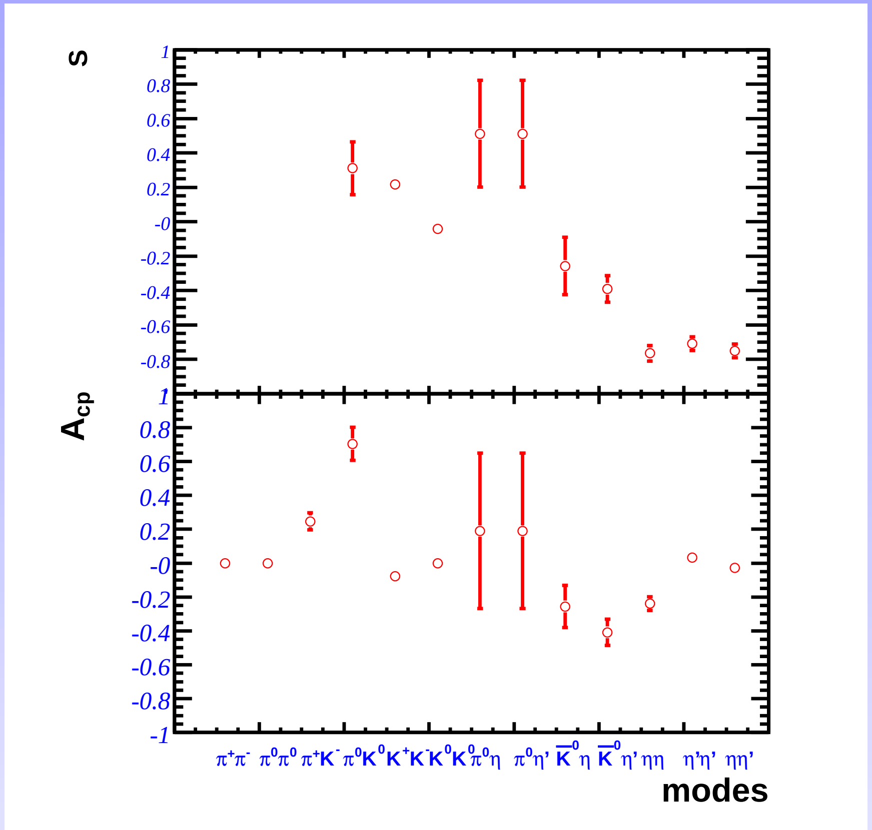
phase angles

- √ larger $\gamma = (77 \pm 4)^\circ$
- √ same $\beta = (23 \pm 2)^\circ$
- √ smaller $\alpha = (80 \pm 6)^\circ$
- √ larger size of UT

Goodness of fit $\chi^2/dof = 32.9/22$

SM predictions for B_s modes





- ✓ Predicted K^+K^- is well bellow the CDF data
- ✓ Large $\eta'\eta'$ is a consequence of large S.

Fit with new physics in πK

Adding a new amplitudes to the electroweak penguin sector

$$V_{ts}V_{td}^*P_{EW} \to V_{ts}V_{td}^*P_{EW} + |V_{ts}V_{td}^*|Ne^{i(\phi+\delta)}$$

Result: large $N/P_{EW} \simeq 3.3$

$$N = 0.04 \pm 0.008, \phi_N = (92 \pm 4)^\circ, \delta_N = (-14 \pm 5)^\circ$$

χ^2/dof drops from 16.4/12 to 4.3/10

Large N/P_{EW} driven by

- √ tension between $\pi\pi$ and πK data on C/T.
- √ Low value of $S(\pi^0 K_S)$

When fit with $P\eta^{(\prime)}$ modes, we find

$N = 0.001 \pm 0.005$ compatible with zero.

Summary

- Falvor $SU(3)$based global fits for charmless $B \to PP$ show an overall agreement with the SM. The results favor a C/T lager than the theoretical expectations with significant strong phase difference. The A_{CP} "puzzle" can be accommodated but not the low $S(\pi^0 K_S)$ which is the main source of the inconsistency.
- $B \to PP$ modes favor a larger γ and J_{CP}, especially when $K\eta^{(\prime)}$ modes are included.
- From data fitting point of view, a new physics amplitude associated with P_{EW} can greatly improve the agreement with the $\pi^0 K_S$ data. However no significant effects are found in fits with $P\eta^{(\prime)}$ modes.