CKM 2008

5th Workshop on the Unitarity Triangle

Roma, Italy ** September 9-13, 2008

Test of Flavor SU(3) Symmetry and Weak Phase γ from $B_{u,d,s} \to K \pi$ Decays

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Outline

- Flavor symmetry and rare *B* decays
- SU(3) and U-spin symmetry global fits
- Tests of flavor SU(3) symmetry
- Problem in $B_{u,d,s} \to K\pi$ decays
- Summary

Flavor SU(3) Symmetry

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

- Flavor SU(3) symmetry principle can be employed to relate/reduce hadronic parameters in charmless *B* decays.
- The flavor symmetry approach:
  - is less model dependent;
  - only concerns with the *flavor flow* (nonperturbative in strong interactions);
  - has a clearer *weak phase structure* (unlike isospin analysis where different weak phases usually mix).

Flavor SU(3) Symmetry

- At the *B* meson mass scale, tiny differences among the light quarks should be immaterial.
  $\Rightarrow$ Treat (u,d,s) as a triplet of the $SU(3)_F$ group.
- Except for weak couplings, the underlying strong dynamics should not distinguish *u*, *d*, and *s* in diagrams of the same topology in flavor flows.
- Relate two types of rare decay amplitudes and associated strong phases using the symmetry:
  strangeness-conserving ($\Delta S = 0$, $b \to q\bar{q}d$); and
  strangeness-changing ($|\Delta S| = 1$, $b \to q\bar{q}s$).
- 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.

Flavor SU(3) Symmetry

- Based on the symmetry, weak interactions of the *B* decays can thus be easily represented by the so-called flavor (or quark or topological) diagrams.
- Such diagrams have already built in with final-state rescattering effects.
- One needs to assume a certain hierarchy (based on some naïve expectations and dynamical arguments) among the amplitudes to pick out dominant ones in the analyses. [For example, it is a common practice to neglect color-suppressed EWP, annihilation, exchange, etc diagrams.]

- A natural question: How good is the flavor symmetry?

Testing Flavor Symmetry

- Results of such an approach are largely driven by data.
- Even though one cannot provide a dynamical understanding of hadronic parameters (amplitude sizes and strong phases) within this framework, a satisfactory fit to the data using the flavor symmetry analysis with small breaking effects could serve as a bottom line.
- We can examine the flavor SU(3) principle by paying particular attention to closely related decay modes.

Flavor SU(3) Breaking

- To account for the fact that $SU(3)_F$ is only an approximate symmetry, breaking factors are usually introduced between amplitudes of the same topology (but keeping the strong phases the same):

SU(3)-breaking paras.

$$
\begin{aligned}
t &\equiv Y_{db}^{u} T & \qquad t' &\equiv Y_{sb}^{u} \xi_t T \\
c &\equiv Y_{db}^{u} C - (Y_{db}^{u} + Y_{db}^{c}) P_{EW} & \qquad c' &\equiv Y_{sb}^{u} \xi_c C - (Y_{sb}^{u} + Y_{sb}^{c}) P_{EW} \\
p &\equiv -(Y_{db}^{u} + Y_{db}^{c}) P & \qquad p' &\equiv -(Y_{sb}^{u} + Y_{sb}^{c}) \xi_p P
\end{aligned}
$$

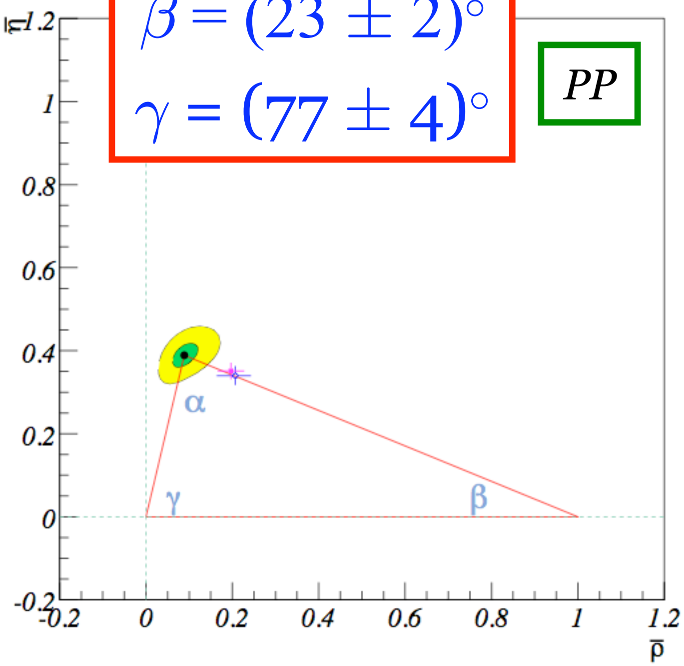
- For factorizable amps (e.g., *T* and *C*), a dominant symmetry breaking factor is f_K/f_π and is at ~20% level. But whether the penguin amplitude can be factorized is more questionable.
- Our fits are pretty stable in the CKM part against different SU(3) symmetry breaking schemes.

Constraints on UT Vertex

- Using global fits to the $B \to PP$ and VP decays within the flavor SU(3) framework, we obtain

$$\alpha = (80 \pm 6)^\circ$$
$$\beta = (23 \pm 2)^\circ$$
$$\gamma = (77 \pm 4)^\circ$$

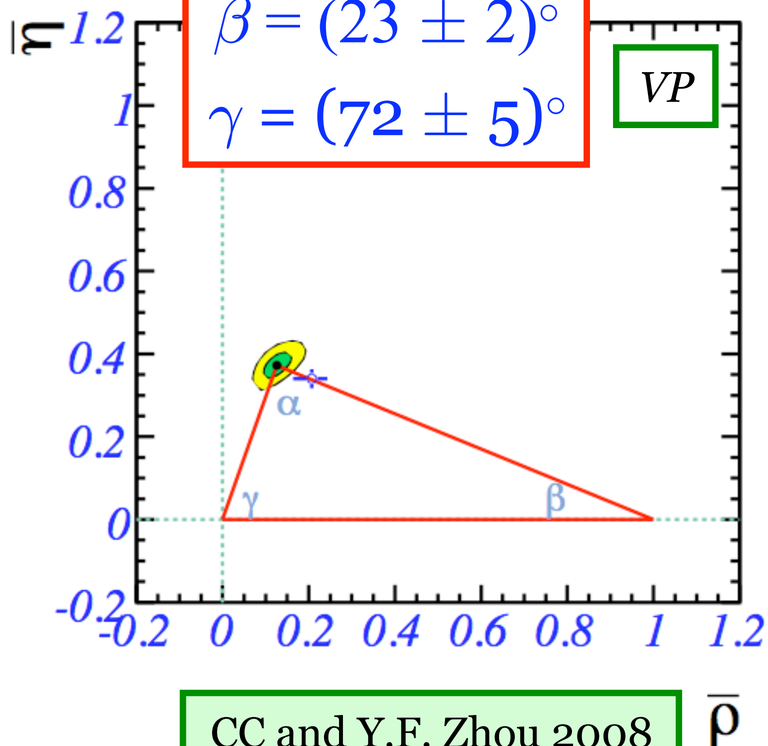
PP



CC and Y.F. Zhou 2006

$$\alpha = (86 \pm 6)^\circ$$
$$\beta = (23 \pm 2)^\circ$$
$$\gamma = (72 \pm 5)^\circ$$

VP



CC and Y.F. Zhou 2008

U-Spin Symmetry

Soni & Suprun 2006, 2007

- An alternative approach utilizes the U-spin symmetry to analyze two-body rare B decays. $\Rightarrow$ (d,s): doublet in the SU(2), subgroup of $SU(3)_F$.
- No amplitude hierarchy needs to be assumed (*cf.* isospin) and thus no approximation is made.
- U-spin breaking still needs to be addressed.

TABLE II. Results of the U-spin fits to charged and neutral subsets of charmless $B \to M_1 M_2$ decays. The bottom panel shows γ as determined from direct measurements in $B \to D^{(*)} K^{(*)}$ decays, from indirect constraints on the apex of the unitarity triangle, and from SU(3) fits to charmless PP and VP decays, for comparison purposes.

Fit	Subset	χ^2/dof	γ
1.	$B^+ \to P^0 P^+$	3.2/4	$(81^{+36}_{-18})°$
2.	$B^0, B_s \to P^- P^+$ (two minima):	3.6/1	$(80^{+6}_{-8})°$
		3.7/1	$(37 \pm 3)°$
3.	$(B^+ \to P^0 P^+) \bigcup (B^0, B_s \to P^- P^+)$	6.8/6	$(80^{+6}_{-8})°$
Direct measurements, *BABAR* [30]			$(67 \pm 28 \pm 13 \pm 11)°$
Direct measurements, Belle [31]			$(53^{+15}_{-18} \pm 3 \pm 9)°$
Indirect constraints, CKMFitter [32]			$(59.8^{+4.9}_{-4.2})°$
Indirect constraints, UTFit [33]			$(61.3 \pm 4.5)°$
SU(3) fits to VP decays [4]			$(66.2^{+3.8}_{-3.9} \pm 0.1)°$
SU(3) fits to PP decays [4]			$(59 \pm 9 \pm 2)°$

Some Simple Tests on Flavor Symmetry

- 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 $|V_{cd}/V_{cs}|$.
- At ICHEP 2008, Belle reports a new measurement $BR(B^+ \to \underline{K}^{*0} K^+) = (0.68 \pm 0.16 \pm 0.10) \times 10^{-6}$ (involving p_P only) at 4.4σ. This also agrees with SU(3) expectation of about 0.5×10^{-6}.
- This partly justifies our use of $SU(3)_F$ as the working assumption in global fits and that factors such as f_K / f_π are not preferred when relating penguin-type amplitudes.
- A more sophisticated case is a set of $B_{u,d,s} \to K\pi$ decays.

Extraction of γ from $B_{u,d,s} \to K\pi$

Gronau & Rosner 2000; CC & Wolfenstein 2000

- It has been proposed to extract the weak phase γ from the the combination of $B_{u,d,s} \to K\pi$ modes, utilizing all the branching ratio and CP asymmetry observables.
- If one uses γ as constrained from other methods (*e.g.*, DK modes), one may as well turn the argument around to test the flavor symmetry assumption.

- Note: there are also many other methods that extract γ using charmless B decay to strange final states ($K\pi$, $K^*\pi$, ρK, etc).

Neubert & Rosner 1998;
Gronau & Rosner 2002, 2003;
Sun 2003; CC 2005

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

- Flavor decomposition of the modes is

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

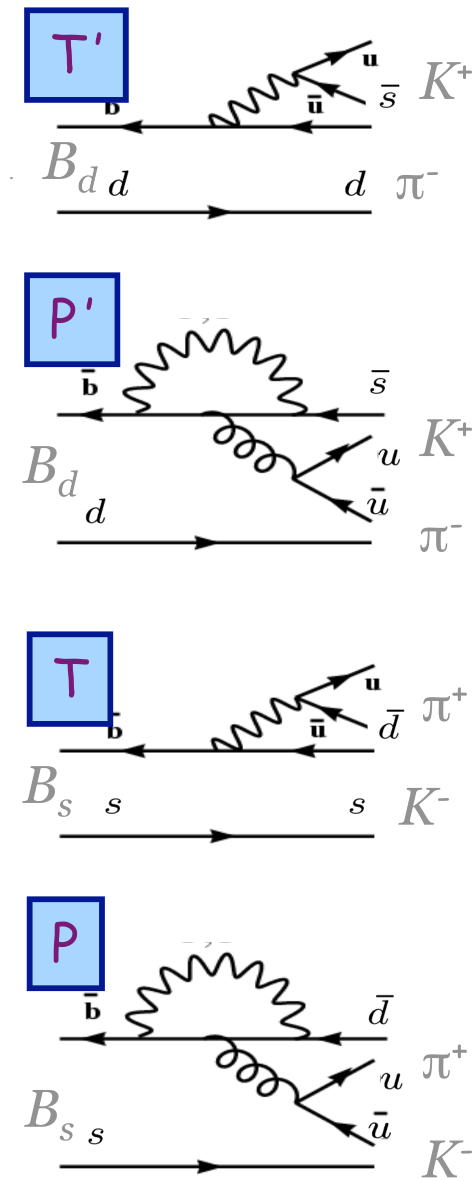
$$\left(\tilde{\lambda} \equiv \left|\frac{V_{us}}{V_{ud}}\right| \simeq 0.2317\right)$$

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

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

corresponding to exact symmetry.

PDG 2006; Khodjamirian et. al. 2003, 2004



Experimental Observables

CC, Gronau & Rosner 2008

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

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

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

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

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

- There are five unknowns (r, γ, δ_d, δ_s, ξ). [$r \equiv |T/P|$]
- Data used in the analysis (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

Relation between Strong Phases

- 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.

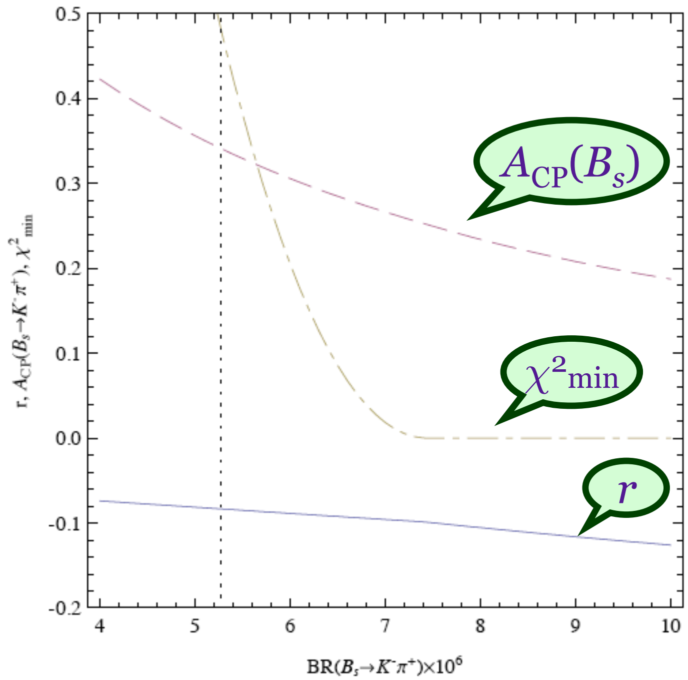
Remarks

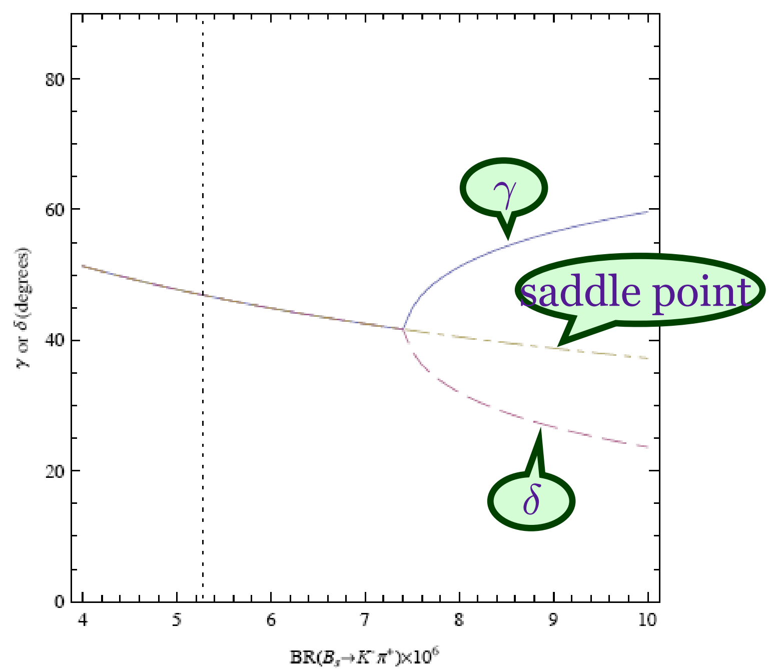
- As the branching ratios of $B^+ \to K^0 \pi^+$ and $B_d \to K^+ \pi^-$ have been determined about 5%, their current central values are not likely to vary much in the future.
- In contrast, the branching ratio and CPA of $B_s \to K^- \pi^+$ are only recently measured by the CDF Collaboration for the first time. CDF 2008
- Note that the quoted value of BR($B_s \to K^- \pi^+$) depends on the fragmentation fractions f_s and f_d, whose ratio carries a 14% uncertainty. Aaltonen et. al. 2008
- Expecting more precise determination of BR($B_s \to K^- \pi^+$) in the coming years, we discuss how it can be fitted into the picture.

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 $BR(B_s \to K^- \pi^+) < 7.5 \times 10^{-6}$, calling for a larger BR or ξ.

$\gamma \leftrightarrow \delta$ symmetry





Solving All 4 Eqs.

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

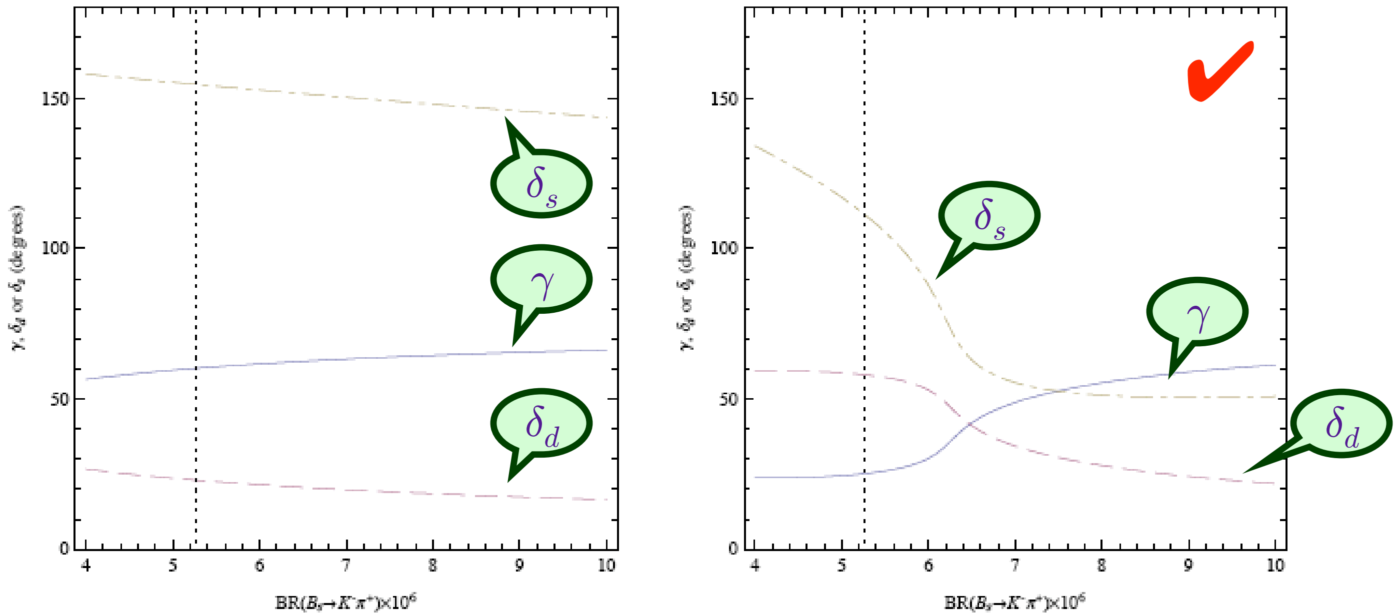


Figure 3: Behavior of solutions as a function of $\mathcal{B}(B_s \to K^- \pi^+)$, assuming $r < 0$. There are two sets of solutions (left and right) when δ_d and δ_s are treated as independent parameters. The solid, dashed and dash-dotted curves represent γ, δ_d and δ_s, respectively. The vertical dotted 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 would be suggested if recent evaluations of *b* quark fragmentation had over-estimated the fraction of *b* quarks ending up as B_s.

Summary

- Despite success in global fits to current data, it is worth scrutinizing the application of flavor symmetry to a limited set of closely related decay modes.
- Comparison of the $B^0 \to K^0 \underline{K}^0$, $B^+ \to K^+ K^0$, and $B^+ \to K^0 \pi^+$ modes shows that SU(3) is a good symmetry.
- Examination of the $B_{u,d,s} \to K\pi$ modes indicates some problem. The flavor symmetry is respected better if:
  - BR($B_s \to K^- \pi^+$) is at least 42% larger than its current central value or, equivalently, the SU(3)-breaking factor is bigger than 1.2; and/or
  - the fraction of b quarks ending up as the B_s meson has been overestimated.
- A constraint on γ using these $K\pi$ modes still waits for improved data.

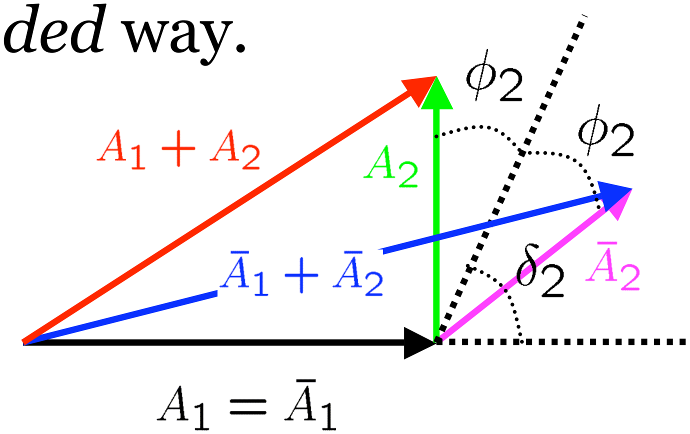
Backup Slides

CP Violation and Rare *B* Decays

- One important objective in the flavor program is to study CP violation in the SM, understand its origin(s), and eventually discover new physics.
- Beauty physics has helped us a lot in this direction from the hadronic mixing and decay phenomena.
- In particular, charmless two-body hadronic *B* decay modes are often sensitive to $V_{\rm td}$ (mixing) and/or $V_{\rm ub}$ (decay).
- Information of weak phases in the UT are often 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.

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

Bander, Silverman & Soni 1979

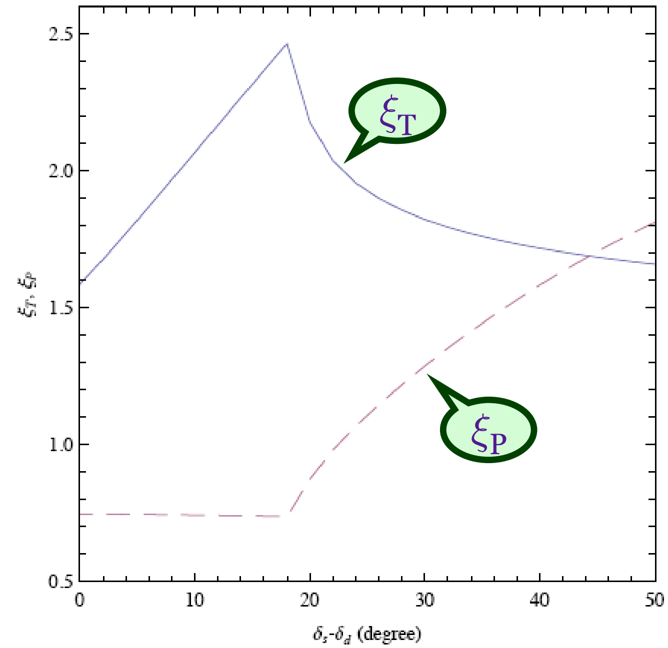
- Large strong phases are usually obtained from model calculations of final-state rescattering effects.

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

- There is still no unanimously agreed systematic way of computing strong phases from first principles.

Different Scalings

- Suppose *T* and *P* are allowed to scale independently (ξ_T and ξ_P) and be different from the factorization prediction.
- Fixing $\xi_T = \xi$ while varying ξ_P does not improve the situation (δ_s too large and γ too small).
- Fixing $\xi_P = \xi$ instead, the situation improves with an increasing ξ_T.



- Fix $\gamma = (67.6 \pm 4.5)^\circ$ [CKMfitter] and vary both ξ_T and ξ_P.
- No perfect solution for $\delta_s - \delta_d < 20^\circ$.
- When $\delta_s - \delta_d \geq 20^\circ$, (r, δ_d) becomes fixed at (-0.182, 15°).