CP Violation: A New Era

Ringberg Phenomenology Workshop
on Heavy Flavors
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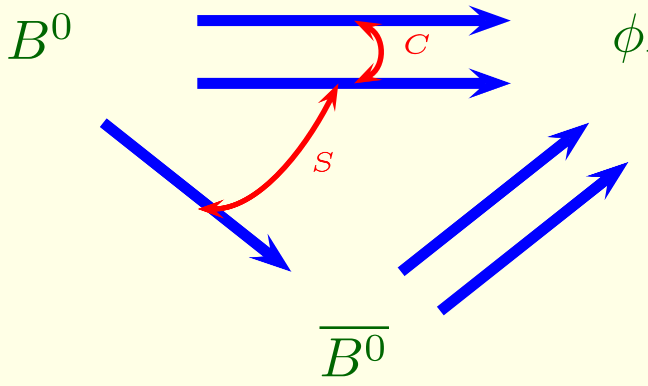
Motivation



$\phi K_S, \eta' K_S, KKK, DD, \psi\pi, \pi\pi$

$f_{\rm CP}$	$b \to q\bar{q}q'$	$-\eta_{\rm CP} S = \pm \frac{2\mathcal{I}m\lambda}{1+\lvert\lambda\rvert^2}$	$C = \frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}$
ψK_S	$b \to c\bar{c}s$	$+0.73 \pm 0.05$	$+0.05 \pm 0.04$
ϕK_S	$b \to s\bar{s}s$	-0.39 ± 0.41	-0.17 ± 0.67
$\eta' K_S$	$b \to s\bar{s}s$	$+0.33 \pm 0.34$	-0.08 ± 0.18
$K^+K^-K_S$	$b \to s\bar{s}s$	$+0.52 \pm 0.47$	$+0.42 \pm 0.37$
$D^{*+}D^{*-}$	$b \to c\bar{c}d$	-0.31 ± 0.46	$+0.02 \pm 0.27$
$\psi\pi$	$b \to c\bar{c}d$	$+0.46 \pm 0.49$	$+0.31 \pm 0.29$
$\pi\pi$	$b \to u\bar{u}d$	$+0.48 \pm 0.61$	-0.51 ± 0.24

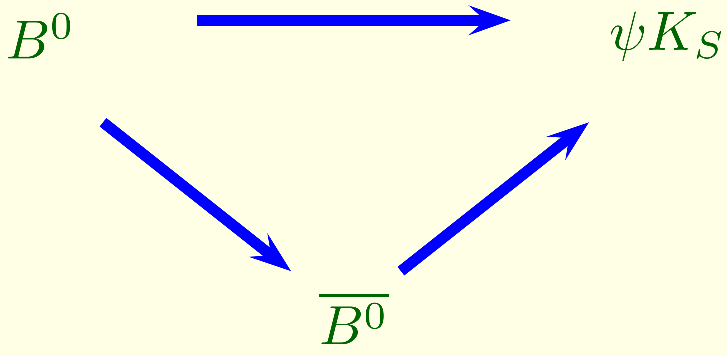
A lot of new data!

Plan of Talk

1. CP asymmetries in $b \to c\bar{c}s$, $b \to s\bar{s}s$
   hep-ph/0208080

2. SU(3) relations and $S_{\eta' K_S}$, $S_{\phi K_S}$, $S_{K^+K^-K_S}$
   hep-ph/0303171

3. The CP Asymmetry in semileptonic B decays
   hep-ph/0202010



- Within SM, dominated by a single phase $\Longrightarrow$ $\boxed{C_{\psi K_S} = 0}$ (Subleading phase is CKM- and loop-suppressed)
- Within SM, $M_{12}^* \propto (V_{tb}^* V_{td})^2$, $A \propto V_{cb}^* V_{cd}$ $\Longrightarrow$ $\boxed{S_{\psi K_S} = \sin 2\beta}$
- With NP, still $S_{\psi K_S} \simeq \sin[\arg(M_{12}^*) - 2\arg(V_{cb}^* V_{cd})]$ and $C_{\psi K_S} \simeq 0$, but $S_{\psi K_S} \neq \sin 2\beta$ is possible.
- BABAR and BELLE measure

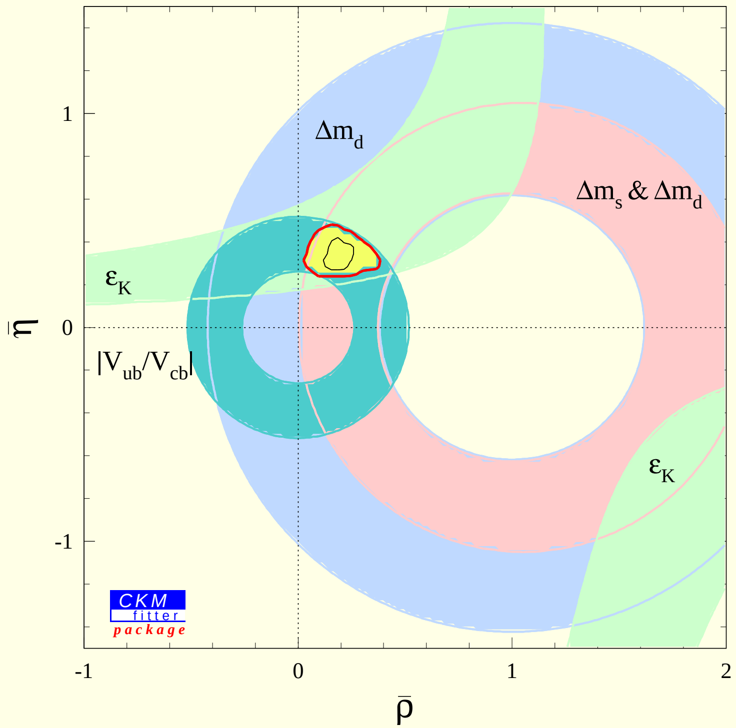
mode	$-\eta_{\psi K} S_{\psi K}$	$C_{\psi K}$
ψK_S	$+0.73 \pm 0.06$	0.05 ± 0.04

Lessons from $\mathcal{A}_{\rm CP}(B \to \psi K_S)$

- CPV in B decays has been observed.
- The Kobayashi-Maskawa mechanism of CPV has successfully passed its first precision test.
- A significant constraint on the CKM parameters $(\bar\rho, \bar\eta)$:

$$\boxed{\mathcal{I}m\lambda_{\psi K_S} = \sin 2\beta = \frac{2\bar\eta(1-\bar\rho)}{\bar\eta^2+(1-\bar\rho)^2} = 0.734 \pm 0.054}$$

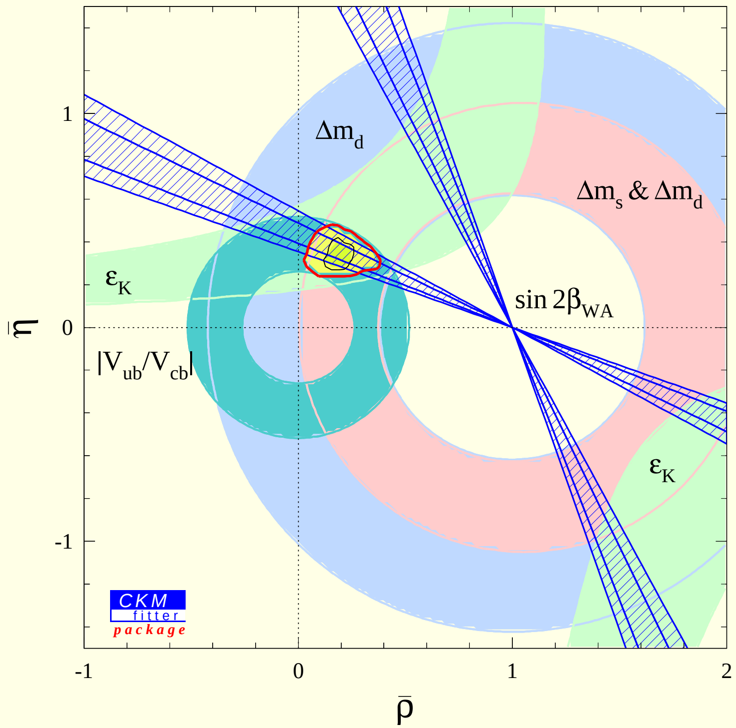
- Approximate CP (in the sense that all CPV phases are small) is excluded.
- New, CPV physics that contributes $> 20\%$ to $B^0 - \overline{B^0}$ mixing is disfavored.



Without $S_{\psi K}$

$\Delta m_B, \;\; \Delta m_{B_s}, \;\; \varepsilon$

Using CKMFitter package (Höcker *et al.*, Eur. Phys. J. C21, 225 (01))



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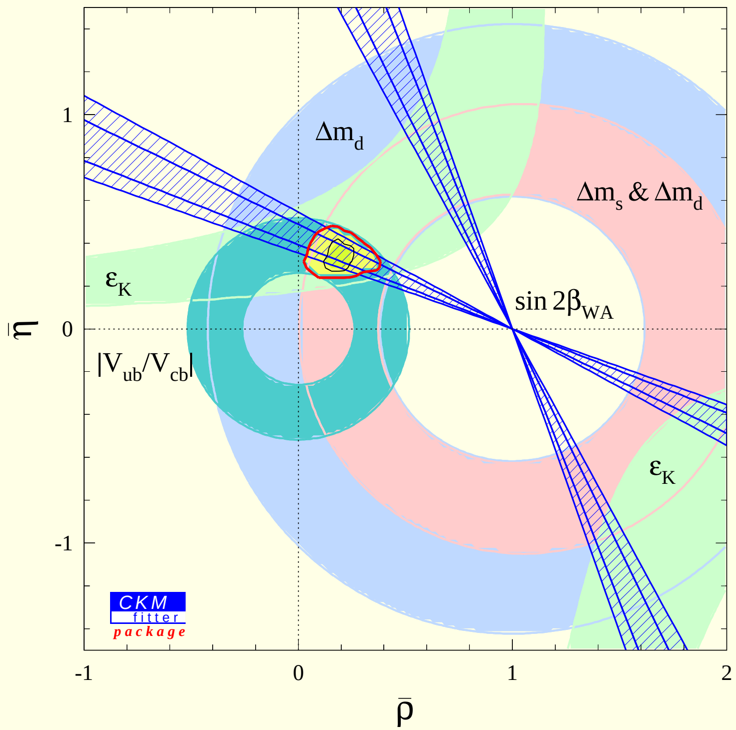
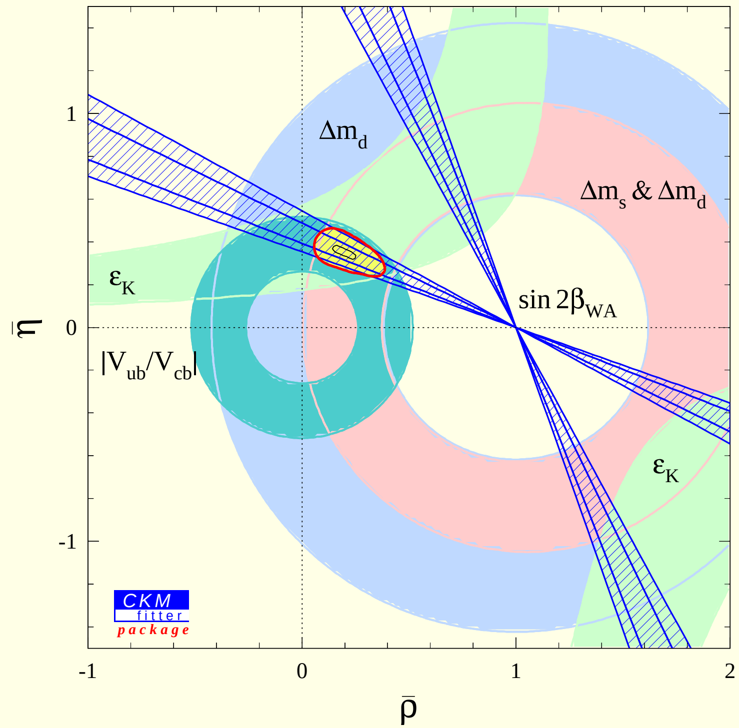
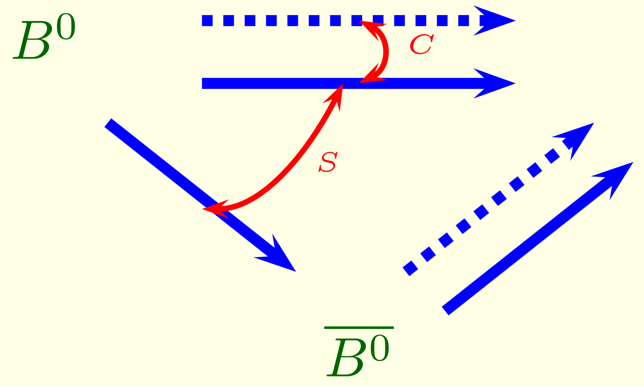




Without $S_{\psi K}$ — $\Delta m_B, \ \Delta m_{B_s}, \ \varepsilon$

With $S_{\psi K}$ — $\Delta m_B, \ \Delta m_{B_s}, \ \varepsilon, \ S_{\psi K_S}$

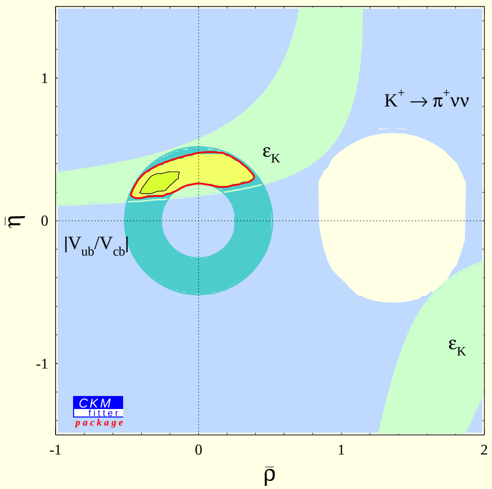
Using CKMFitter package (Höcker *et al.*, Eur. Phys. J. C21, 225 (01))



- Within SM, dominated by a single phase $\Longrightarrow$ $\boxed{C \approx 0}$
  (Subleading phase is CKM-suppressed)
- Within SM, $A \propto V_{cb}^* V_{cd}$ $\Longrightarrow$ $\boxed{S \approx S_{\psi K_S} (\approx +0.73)}$
- With NP, $S \neq S_{\psi K_S}$, $S_{f_1} \neq S_{f_2}$ and $C \neq 0$ are possible.

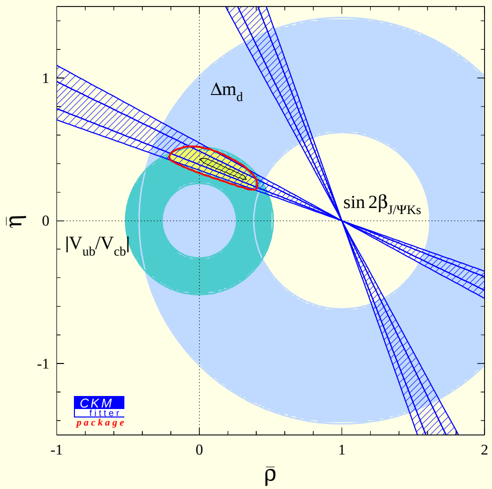
mode	$-\eta S$	C
ϕK_S	-0.39 ± 0.41	-0.17 ± 0.67
$\eta' K_S$	$+0.33 \pm 0.34$	-0.08 ± 0.18
$K^+ K^- K_S$	$+0.52 \pm 0.47^{+0.27}_{-0.03}$ *	$+0.42 \pm 0.37^{+0.22}_{-0.03}$

* Isospin analysis is used to argue CP = + dominance.



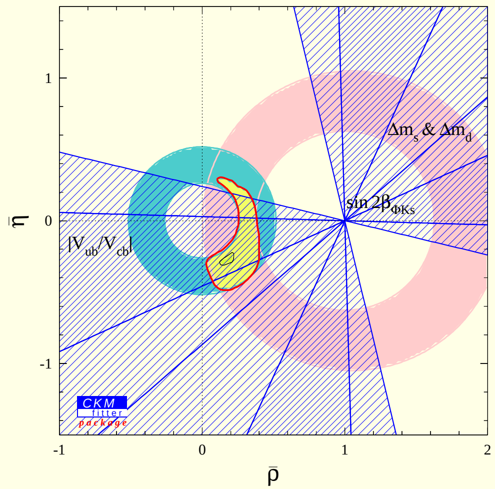
$s \to d$

$\varepsilon, \quad \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$



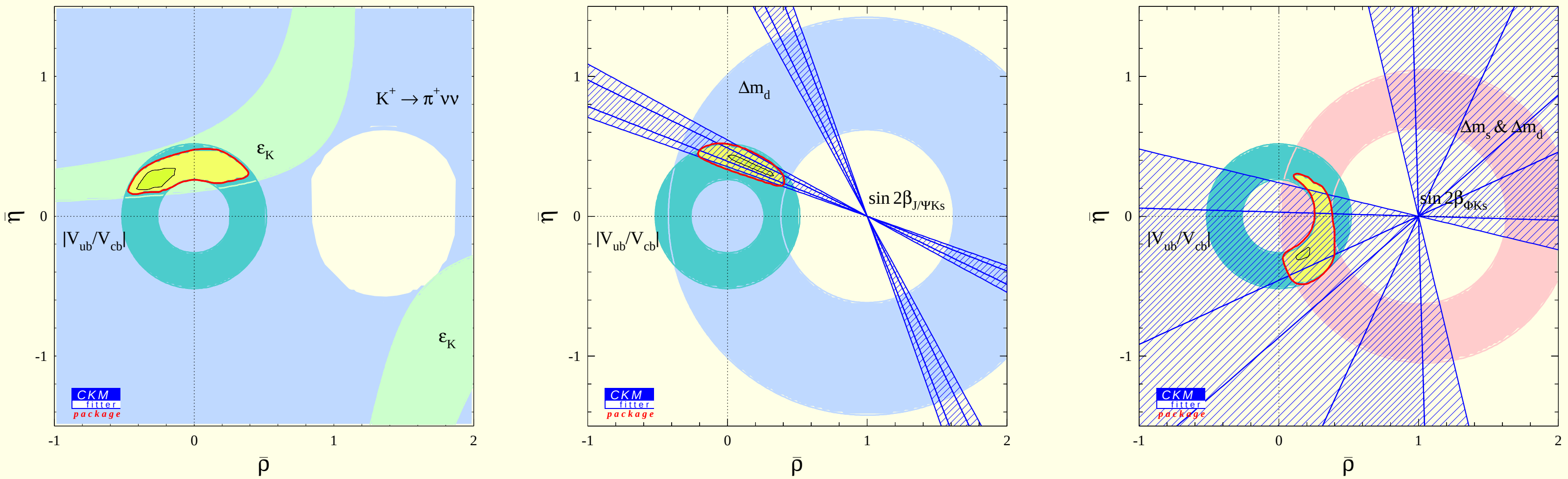
$b \to d$

$\Delta m_{B_d}, \quad S_{\psi K_S}$



$b \to s$

$\Delta m_{B_s}, \quad S_{\phi K_S}$



$s \to d$	$b \to d$	$b \to s$
$\varepsilon, \ \ \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$\Delta m_{B_d}, \ \ S_{\psi K_S}$	$\Delta m_{B_s}, \ \ S_{\phi K_S}$

There is still a lot to be learnt from future measurements

It is still possible that corrections to SM are large in Δm_{B_s}, in CP asymmetries in B_s decays, and in $\mathcal{I}m\lambda_{(\bar{s}s)K_S}$.

The Question

- Within SM, there is a second, CKM suppressed, phase:
  $A_{\eta' K_S} = V_{cb}^* V_{cs} a^c_{\eta' K_S} + V_{ub}^* V_{us} a^u_{\eta' K_S}$
  $\Longrightarrow S_{\eta' K_S} - \sin 2\beta = 2\cos 2\beta \sin\gamma \cos\delta \; |\xi_{\eta' K_S}|$
  $\xi_{\eta' K_S} \equiv \frac{V_{ub}^* V_{us} \; a^u_{\eta' K_S}}{V_{cb}^* V_{cs} \; a^c_{\eta' K_S}}$

- How large can $\xi_{\eta' K_S}$ be?
  - $\mathcal{O}(\lambda^2)$ [CKM suppression]
  - Quark model [London and Soni, hep-ph/9704277: ~ 0.02]
  - BBNS [Beneke and Neubert, hep-ph/0210085: ~ 0.07]
  - SU(3) relations [GLNQ, hep-ph/0303171]

The Strategy

- For $b \to q\bar{q}s$ transitions:
  $A_f = V_{cb}^* V_{cs}\ a_f^c + V_{ub}^* V_{us}\ a_f^u = V_{cb}^* V_{cs}\ a_f^c (1 + \xi_f)$
- For $b \to q\bar{q}d$ transitions:
  $A_{f'} = V_{cb}^* V_{cd}\ b_{f'}^c + V_{ub}^* V_{ud}\ b_{f'}^u = V_{ub}^* V_{ud}\ b_{f'}^u (1 + \lambda^2 \xi_{f'}^{-1})$
- SU(3) gives relations among the $a_f^q, b_{f'}^q$:
  $a_f^u = \sum_{f'} x_{f'}\ b_{f'}^u$
- The branching ratios $\mathcal{B}(f)$ constrain $a_f^c, b_{f'}^u$:
  $\frac{|V_{ud} V_{ub}| b_{f'}^u}{|V_{cs} V_{cb}| a_f^c} \sim \sqrt{\frac{\mathcal{B}(f')}{\mathcal{B}(f)}}$
- Combining SU(3) and experimental data gives, conservatively,
  $$|\xi_f| = \frac{|V_{us} V_{ub}| a_f^u}{|V_{cs} V_{cb}| a_f^c} < \left|\frac{V_{us}}{V_{ud}}\right| \sum_{f'} |x_{f'}| \sqrt{\frac{\mathcal{B}(f')}{\mathcal{B}(f)}}$$

SU(3) decomposition for $\langle P_8 P_8|(\bar{b}u)(\bar{u}q)|B^0\rangle$

$f^{(\prime)}$	A^{27}_{15}	A^{8}_{15}	$A^{8}_{\bar{6}}$	A^{8}_{3}	A^{1}_{3}
$\eta_8 K^0$	$4\sqrt{6}/5$	$1/\sqrt{6}$	$-1/\sqrt{6}$	$-1/\sqrt{6}$	0
$\eta_8 \pi^0$	0	$5/\sqrt{3}$	$1/\sqrt{3}$	$-1/\sqrt{3}$	0
$\pi^0\pi^0$	$-13/5$	$1/2$	$1/2$	$1/6$	1
$\eta_8\eta_8$	$3/5$	$-1/2$	$-1/2$	$-1/6$	1
$\pi^-\pi^+$	$14/5$	1	1	$1/3$	2
K^-K^+	$-2/5$	2	0	$-2/3$	2
$K^0\overline{K^0}$	$-2/5$	-3	-1	$1/3$	2

- SM: 5 SU(3)-amplitudes describe 15 final states

$\Longrightarrow$ Many relations among the matrix elements

The Answer

For example, $(s = \sin\theta_{\eta\eta'}, \quad c = \cos\theta_{\eta\eta'})$

$$a^u_{\eta' K^0} = \frac{s^2 - 2c^2}{2\sqrt{2}}\, b^u_{\eta'\pi^0} - \frac{3cs}{2\sqrt{2}}\, b^u_{\eta\pi^0} + \frac{\sqrt{3}s}{2\sqrt{2}}\, b^u_{\pi^0\pi^0} - \frac{\sqrt{3}s(1+c^2)}{2\sqrt{2}}\, b^u_{\eta'\eta'} + \frac{\sqrt{3}sc^2}{2\sqrt{2}}\, b^u_{\eta\eta} + \frac{\sqrt{3}c^3}{\sqrt{2}}\, b^u_{\eta\eta'}$$

$$\Longrightarrow \quad |\xi_{\eta' K_S}| < \left|\frac{V_{us}}{V_{ud}}\right| \left[0.59\sqrt{\frac{\mathcal{B}(\eta'\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.33\sqrt{\frac{\mathcal{B}(\eta\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.20\sqrt{\frac{\mathcal{B}(\pi^0\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.39\sqrt{\frac{\mathcal{B}(\eta'\eta')}{\mathcal{B}(\eta' K^0)}} + 0.18\sqrt{\frac{\mathcal{B}(\eta\eta)}{\mathcal{B}(\eta' K^0)}} + 1.03\sqrt{\frac{\mathcal{B}(\eta\eta')}{\mathcal{B}(\eta' K^0)}}\right].$$

$$\Longrightarrow \quad \boxed{|\xi_{\eta' K_S}| \lesssim 0.3}$$

Another Strategy

For ϕK: Grossman, Isidori, Worah, hep-ph/9708305

- Similar relations hold for the charged mode ($x =$ free):

$$a_{\eta' K^+} = \frac{(3-x)cs}{2}\, b_{\eta\pi^+} + \frac{(x-1)s^2 + 2c^2}{2}\, b_{\eta'\pi^+} + \frac{(x-3)s}{2\sqrt{3}}\, b_{\pi^+\pi^0} + \frac{xs}{\sqrt{6}}\, b_{\overline{K^0}K^+}$$

- Using experimental data, we obtain $|\xi_{\eta' K^+}| \lesssim 0.1$
- We have $a^c_{\eta' K^0} = a^c_{\eta' K^+}$ but $a^u_{\eta' K^0} \neq a^u_{\eta' K^+}$. However,

$$\boxed{a^u_{\eta' K^0} = \text{color-suppressed}, \quad a^u_{\eta' K^+} = \text{color-allowed}}$$

- Using the mild dynamical assumption, $a^u_{\eta' K^0} \not> a^u_{\eta' K^+}$

$$\Longrightarrow \quad \boxed{|\xi_{\eta' K_S}| \lesssim 0.1}$$

Results

$$|\xi_{\eta' K_S}| < 0.3 \quad \text{SU(3)}$$

$$|\xi_{\eta' K_S}| < 0.1 \quad \text{SU(3) + leading } N_c \text{ assumption}$$

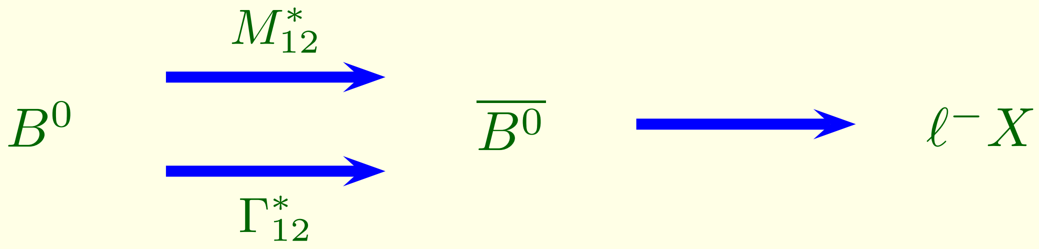
$$|\xi_{\phi K_S}| < 0.25 \quad \text{SU(3) + non-cancellation assumption}$$

$$|\xi_{K^+ K^- K_S}| \sim 0.1 \quad \text{U-spin}$$

Comments

- The same bound applies to $|C_f|$: $C_f \sim 2\sin\gamma\sin\delta\ |\xi_f|$
- The bounds apply also to MFV models
- Our bounds are weaker than estimates based on explicit calculations, but have the advantage of being model independent
- With better data, the bounds will improve
- SU(3) breaking effects could be significant, but our bounds are probably still conservative

If experiments find deviations larger than our bounds $\Longrightarrow$ A convincing case for new physics



- SM $\quad -0.0013 < \mathcal{A}_{\rm SL} < -0.0005$
- MFV $\quad -0.0018 < \mathcal{A}_{\rm SL} < -0.0003$
- NP in loops $\quad -0.004 < \mathcal{A}_{\rm SL} < +0.04$
- Experiments $\quad -0.021 < \mathcal{A}_{\rm SL} < +0.025$

An interesting constraint on the NP parameters $r_d^2,\ \theta_d$

New Physics

1. The 3×3 CKM matrix is unitary
2. Tree level processes are dominated by the SM

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2. Tree level processes are dominated by the SM

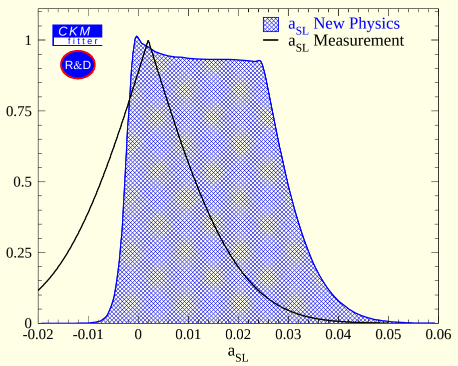
$$\Downarrow$$

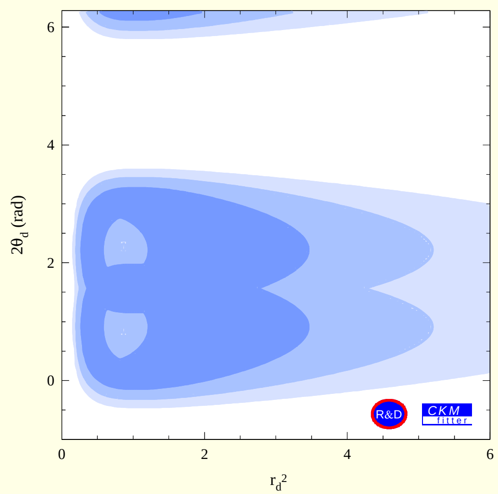
$$\Gamma_{12} = \Gamma_{12}^{\rm SM}$$
$$M_{12} = r_d^2 e^{2i\theta_d} M_{12}^{\rm SM}$$

$$\Downarrow$$

$$\Delta m_B = r_d^2 (\Delta m_B)^{\rm SM}$$
$$S_{\psi K} = \sin(2\beta + 2\theta_d)$$
$$\mathcal{A}_{\rm SL} = -\mathcal{R}e \left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \frac{\sin 2\theta_d}{r_d^2} + \mathcal{I}m \left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \frac{\cos 2\theta_d}{r_d^2}$$

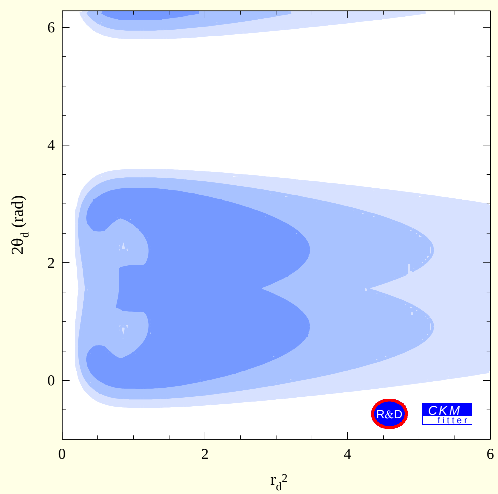
Constraining $r_d^2,\ 2\theta_d$





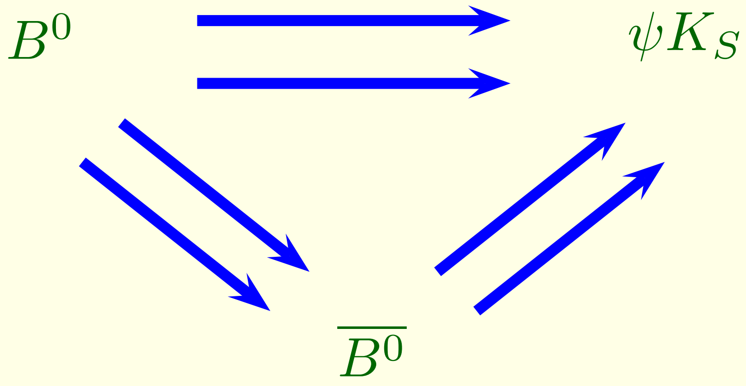
Without $\mathcal{A}_{\rm SL}$

$\Delta m_{B_d},\ S_{\psi K_S}$



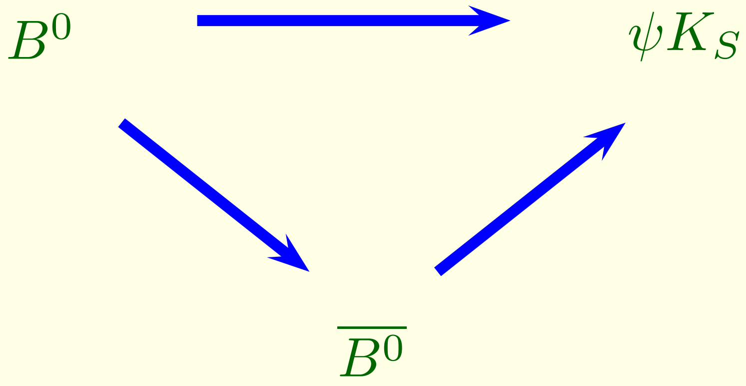
With $\mathcal{A}_{\rm SL}$

$\mathcal{A}_{\rm SL}$



$$|\lambda_{\psi K}| = \left| \frac{q}{p} \frac{\bar{A}_{\psi K}}{A_{\psi K}} \right| = 0.95 \pm 0.04 \; ?$$

$\mathcal{A}_{\rm SL}$



$$|\lambda_{\psi K}| = \left|\frac{q}{p}\frac{\bar{A}_{\psi K}}{A_{\psi K}}\right| = 0.95 \pm 0.04 \ ?$$

$$\mathcal{A}_{\rm SL} = 0.002 \pm 0.014 \implies |q/p| = 0.999 \pm 0.007$$

- CPV in mixing can be safely neglected at present
- $C^{\rm Babar}_{f_{\rm CP}} \equiv -\mathcal{A}^{\rm Belle}_{f_{\rm CP}} \neq 0 \implies$ CPV in decay

$$\mathcal{A}_{\psi K^{\mp}} = 0.008 \pm 0.025 \implies |\bar{A}_{\psi K}/A_{\psi K}| = 1.008 \pm 0.025$$
$$\implies |\lambda_{\psi K}| = 1.007 \pm 0.026 \ !$$

Conclusions

- One 'clean' measurement can teach us a lot!
  $S_{\psi K} \Longrightarrow$ The KM mechanism is, very likely, the dominant source of the observed CPV

- We learn a lot from 'dirty' measurements too!
  - $\mathcal{B}(f)$'s + SU(3) relations $\Longrightarrow$ Model independent constraints on $S_{(\bar{s}s)K_S} - S_{\psi K_S}$
  - $\mathcal{A}_{\rm SL} \Longrightarrow$ Constraints on $r_d^2, 2\theta_d$
  - $\mathcal{A}_{\rm SL} \Longrightarrow$ CPV in mixing ($|q/p| \neq 1$) can be safely neglected in $|\lambda_{f_{\rm CP}}|$

The KM mechanism

- The KM mechanism successfully passed its first precision test

  Very likely, the KM mechanism is the dominant source of CP violation in flavor changing processes

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- 'Very likely': The consistency could be accidental
  $\Longrightarrow$ More measurements of CPV are crucial.
- 'Dominant': There is still room for NP at the $\mathcal{O}(20\%)$ level
  $\Longrightarrow$ A challenge for theorists.
- 'FC processes': FD CPV can still be dominated by NP
  $\Longrightarrow$ Search for EDMs.