Exploring New Physics with B Physics

Workshop on Flavour in the Era of the LHC
CERN – November 7, 2005

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Thanks to:

- Guy Raz
- Stephane Monteil *et al.* (CKMfitter)
- Luca Silvestrini (UTfit)

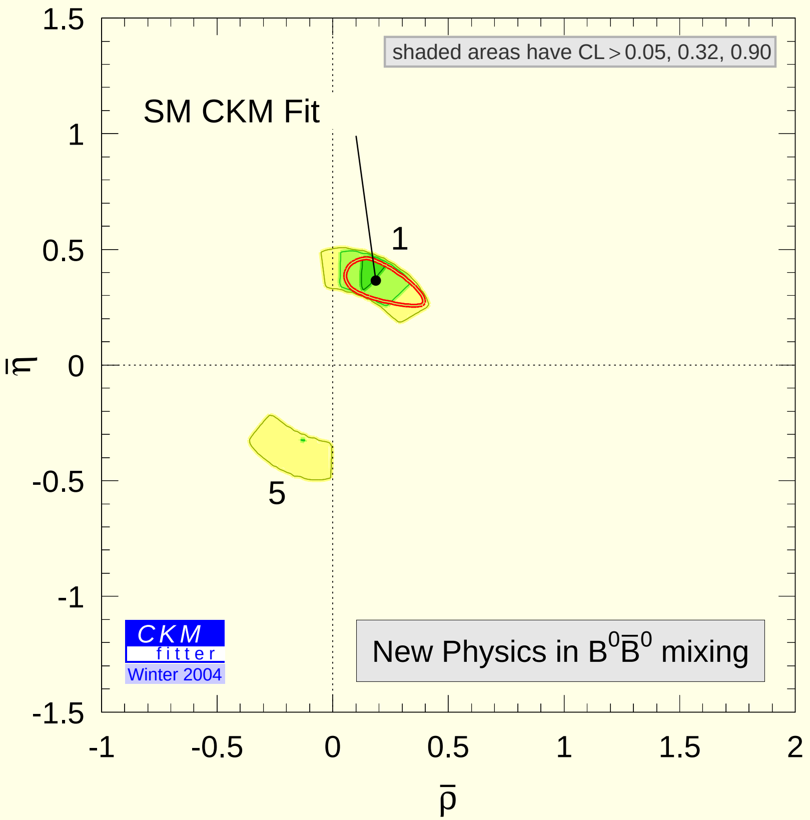
Plan of Talk

1. Recent Era: Excluding alternatives to the KM mechanism
   (a) Is the KM mechanism at work?
   (b) Is $\delta_{\rm KM}$ the only source of CPV in meson decays?
   (c) Is CPV in $K \to \pi\pi$ small because of flavor suppression?
   (d) Is there direct CPV?
   (e) Is there New Physics in $B^0 - \overline{B}^0$ mixing?
   (f) Is there New Physics in $b \to s$ transitions?
2. Future: Looking for corrections to the KM mechanism
   $S_{\pi^0 K_S}$: SM and NP
   (a) Factorization related methods
   (b) SU(3) based methods
   (c) Supersymmetry as an example

Is the KM mechanism at work?

- Assume: New Physics in tree decays - negligible
- Define $r_d^2 \exp(2i\theta_d) = \langle B^0|\mathcal{H}^{\rm full}|\overline{B}^0\rangle / \langle B^0|\mathcal{H}^{\rm SM}|\overline{B}^0\rangle$
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}$
- Fit to $\boxed{\eta}$, ρ, r_d, θ_d
- Find whether $\eta = 0$ is allowed

The KM mechanism is at work!

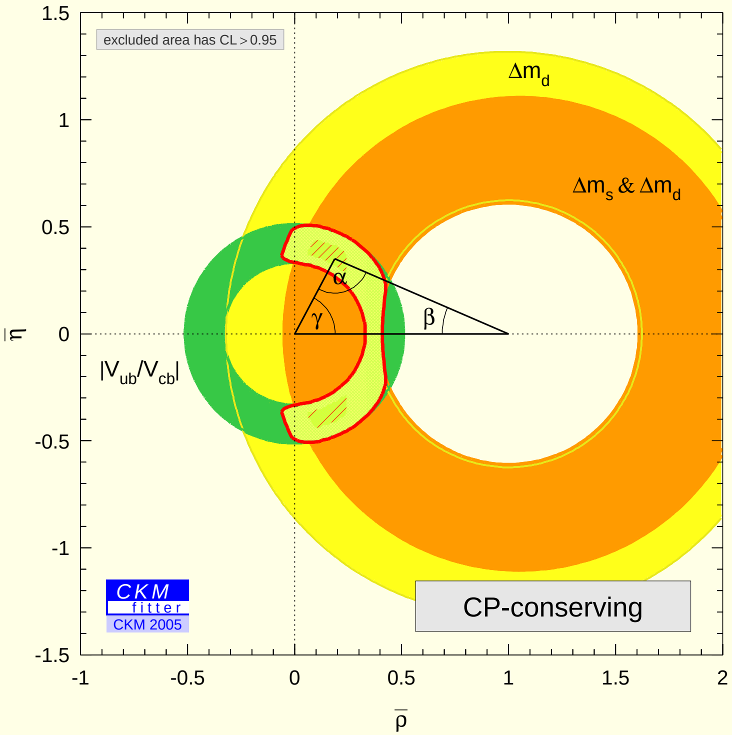


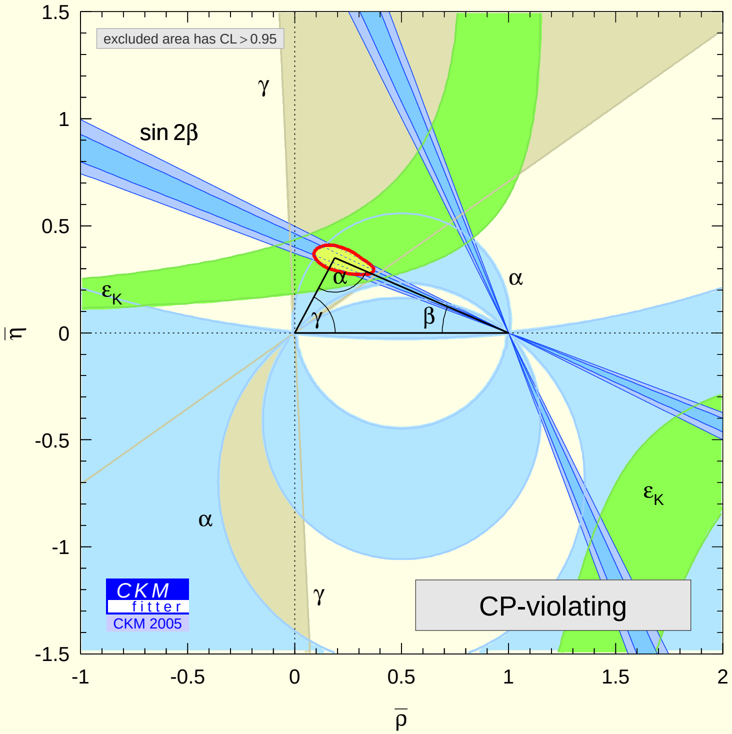
SM tree level + NP in $B^0 - \overline{B}^0$ mixing $(\Delta m_B,\ S_f,\ A_{\rm SL})$

CKMFitter, hep-ph/0406184

$$\boxed{\delta_{\rm KM} \neq 0}$$

Is δ_{KM} the only source of CPV in meson decays?





Tree level + CPC observables

$\Delta m_B, \quad \Delta m_{B_s}$

Tree level + CPV observables

$\varepsilon, \quad S_{\psi K}, \quad \alpha, \quad \gamma$

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

Very likely, $\delta_{\rm KM}$ is dominant!

$S_{\psi K} = +0.69 \pm 0.03 \;\Leftrightarrow\; \sin 2\beta(\text{CKM fit}) = +0.74^{+0.07}_{-0.03}$

> The KM mechanism successfully passed its first precision test

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$$\alpha(\pi\pi, \pi\rho, \rho\rho) = \left[101^{+16}_{-9}\right]^o \;\Leftrightarrow\; \alpha(\text{CKM fit}) = 96 \pm 16^o$$

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The KM mechanism successfully passed its second precision test

$\gamma(DK) = \left[63^{+15}_{-13}\right]^o \;\Leftrightarrow\; \gamma(\text{CKM fit}) = \left[57^{+7}_{-14}\right]^o$

The KM mechanism successfully passed its third precision test

Is CPV in $K \to \pi\pi$ small because of flavor?

SM:

- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

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Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

B Physics:

- $S_{\psi K} \sim 0.7$

$\Longrightarrow$ Some CP violating phases are indeed $\mathcal{O}(1)$

Is CP violated in $\Delta B = 1$ processes?

SM:

- Indirect (M_{12}) and direct (A_f) CP violations are both large

Superweak:

- There is no direct (A_f) CP violation

K Physics:

- $\epsilon'/\epsilon = (1.72 \pm 0.18) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes $(s \to u\bar{u}d)$

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B Physics:

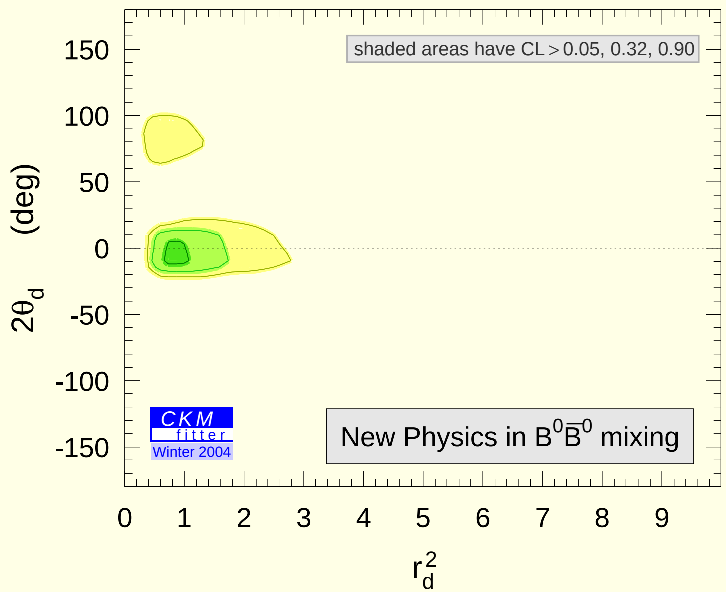
- $\mathcal{A}_{K^{\mp}\pi^{\pm}} = -0.115 \pm 0.018$, $\mathcal{A}_{\rho\pi}^{-+} = -0.48 \pm 0.14$

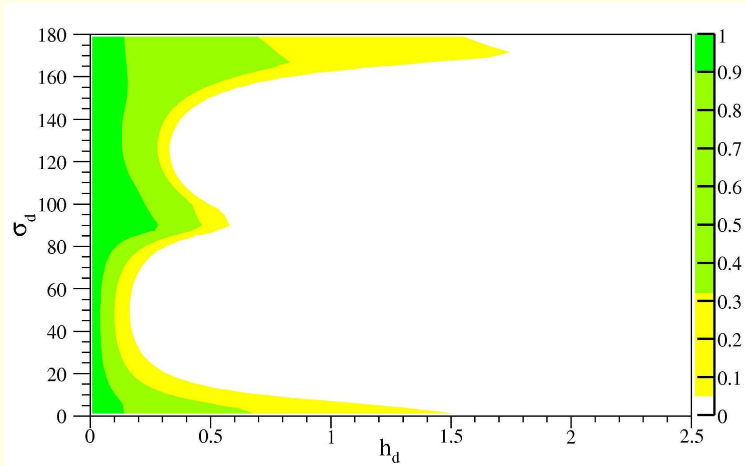
$\Longrightarrow$ CP is violated in $\Delta B = 1$ processes $(b \to u\bar{u}s,\ b \to u\bar{u}d)$

Is there NP in $B^0 - \overline{B}^0$ mixing?

- Assume: New Physics in tree decays - negligible
- Define $r_d^2 \exp(2i\theta_d) \equiv 1 + he^{i\sigma} \equiv \langle B^0|\mathcal{H}^{\rm full}|\overline{B}^0\rangle / \langle B^0|\mathcal{H}^{\rm SM}|\overline{B}^0\rangle$
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}$
- Fit to η, ρ, $\boxed{r_d}$, θ_d (or $\boxed{h}$, σ)
- Find whether $h \neq 0$ $(r_d \neq 1)$ is allowed

Very likely, the KM mechanism dominates





CKMFitter

Agashe et al., hep-ph/0509117

For arbitrary phase, $h = |A_{\rm NP}/A_{\rm SM}| \sim 0.2 \pm 0.2$

Is there NP in $b \to s$ transitions?

- Rare $b \to s$ processes consistent with the SM predictions

$\Longrightarrow$ New Physics contributions to certain operators are strongly constrained (Z-penguin, magnetic)

$\Longrightarrow$ New physics contributions to other operators are still very weakly constrained (chromomagnetic, dim-6)

Is there NP in $b \to s$ transitions?

SM: $\boxed{\Delta S \equiv -\eta_{\rm CP} S - S_{\psi K} \approx 0, \quad C \approx 0}$

$f_{\rm CP}$	ΔS	C
ϕK_S	-0.22 ± 0.19	-0.09 ± 0.15
$\eta' K_S$	$-0.19 \pm 0.09^\dagger$	-0.07 ± 0.07
$f_0 K_S$	$+0.06 \pm 0.24$	$+0.06 \pm 0.21$
$\pi^0 K_S$	-0.38 ± 0.26	-0.02 ± 0.13
ωK_S	-0.06 ± 0.30	-0.44 ± 0.24
$K_S K_S K_S$	-0.09 ± 0.23	-0.31 ± 0.17
$K^+ K^- K_S^\ddagger$	-0.16 ± 0.17	$+0.09 \pm 0.10$

† Belle and Babar not quite consistent ($\Longrightarrow -0.19 \pm 0.13$) ‡ Not a CP eigenstate

$\Longrightarrow$ How good is $\approx$?

Basics

- Formalism:
  - Effective $\mathcal{H}$ for $b \to s q\bar{q}$ decays:
    $\mathcal{H} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{ps}^* V_{pb} \Big(\sum_{i=1}^{2} C_i O_i^p$
    $+ \sum_{i=3}^{10} C_i O_i + C_{7\gamma} O_{7\gamma} + C_{8g} O_{8g} \Big)$
  - Decay amplitudes:
    $A_f = \langle f|\mathcal{H}|B^0\rangle,\ \overline{A}_f = \langle f|\mathcal{H}|\overline{B}^0\rangle,\ \lambda_f = e^{-i\phi_B}(\overline{A}_f/A_f)$
  - CP asymmetries:
    $S_f = 2\mathcal{I}m(\lambda_f)/(1+|\lambda_f|^2),\ C_f = (1-|\lambda_f|^2)/(1+|\lambda_f|^2)$
- SM:
  - $A_f^{\mathrm{SM}} = A_f^c + A_f^u$ with $A_f^c \propto V_{cb}^* V_{cs}$ and $A_f^u \propto V_{ub}^* V_{us}$
  - $A_f^{\mathrm{SM}} = A_f^c (1 + a_f^u e^{i\gamma})$

The Problem

- Simple NP:
  - $C_i(m_W) = C_i^{\rm SM}(m_W) + x_i \varepsilon e^{i\theta}$, x_i known
  - $A_f^{\rm SM} = A_f^c \left[1 + a_f^u e^{i\gamma} + b_f^c \varepsilon e^{i\theta}\right]$
- CP asymmetries:
  - $\Delta S_f = +2\cos 2\beta_{\rm eff} \left[\mathcal{R}e(b_f^c)\varepsilon \sin\theta + \mathcal{R}e(a_f^u)\sin\gamma\right]$
  - $C_f = -2\mathcal{I}m(b_f^c)\varepsilon \sin\theta - 2\mathcal{I}m(a_f^u)\sin\gamma$
- Problem:
  - To be concvinced that $\varepsilon \neq 0$, we need to know a_f^u
  - $a_f^u = |(V_{ub}V_{us})/(V_{cb}V_{cs})| \times$ hadronic parameters

Factorization-related methods

Example: $B \to K^0\pi^0$:

$$A^c_{K^0\pi^0} \approx iV^*_{cb}V_{cs}\frac{G_F}{2} f_K F^{B\to\pi}(m_K^2)(m_B^2 - m_\pi^2)\,(a_4 + r_\chi a_6)\,,$$

$$A^u_{K^0\pi^0} \approx iV^*_{ub}V_{us}\frac{G_F}{2}\left[f_K F^{B\to\pi}(m_K^2)(m_B^2 - m_\pi^2)\,(a_4 + r_\chi a_6) - f_\pi F^{B\to K}(m_\pi^2)(m_B^2 - m_K^2)a_2\right]$$

where $r_\chi = 2m_K^2/[m_b(m_s + m_d)]$, $a_i \equiv C_i + C_{i\pm1}/N_c$

$$\Downarrow$$

$$\boxed{a^u_{K\pi} \approx \lambda^2 R_u \left(1 - \frac{f_\pi}{f_K}\frac{F^{B\to K}}{F^{B\to\pi}}\frac{a_2}{a_4 + r_\chi a_6}\right) \approx 2.75\lambda^2 R_u \approx 0.052}$$

$\Longrightarrow \Delta S_{\pi K_S} \approx 0.06, \qquad C_{\pi K_S} \approx 0$

$\Delta S_{\pi^0 K_S}$ in Factorization-related methods

$\Delta S_{\pi^0 K_S}$	Method	hep-ph/	Authors
$+0.06 \pm 0.04$	NF	0503151	Buchalla, Hiller, Nir, Raz
$+0.04 \pm 0.03$	NF+model	0502235	Cheng, Chua, Soni
$+0.07 \pm 0.04$	QCDF	0505075	Beneke
$+0.06 \pm 0.03$	PQCD	0508041	Li, Mishima, Sanda
$+0.08 \pm 0.16$	SCET+SU(3)	0510241	Bauer, Rothstein, Stewart

SU(3)-based methods

- For $b \to s$, define: $d_f^q = A_f^q / (V_{qb}^* V_{qs})$
  $A_f = V_{cb}^* V_{cs} d_f^c + V_{ub} V_{us}^* d_f^u$
- For $b \to d$, define: $h_{f'}^q = A_{f'}^q / (V_{qb}^* V_{qd})$
  $A_{f'} = V_{cb}^* V_{cd} h_{f'}^c + V_{ub} V_{ud}^* h_{f'}^u$

The approximate SU(3) symmetry of the strong interactions
$\Longrightarrow \quad d_f^q = \Sigma_{f'} X_{f'} h_{f'}^q$
where $X_{f'}$ are known (CG) coefficients

$$\boxed{|a_f^u| = \frac{|V_{ub} V_{us} d_f^u|}{|V_{cb} V_{cs} d_f^c|} \le \left|\frac{V_{us}}{V_{ud}}\right| \frac{\Sigma_{f'} |X_{f'}| \sqrt{\mathcal{B}(B \to f')}}{\sqrt{\mathcal{B}(B \to f)}}}$$

SU(3)-based methods

$\ominus$ SU(3) breaking effects of $\mathcal{O}(0.3)$
$\Longrightarrow$ The bounds are only approximate

$\ominus$ Adding (conservatively) the amplitudes coherently
$+$ Dependence on measured $\mathcal{B}$'s
$\Longrightarrow$ Bounds often much weaker than actual estimates

$\oplus$ Hadronic model independence
$\Longrightarrow$ Complimentary to the factorization-related methods

SU(3)-based methods

Example: $B \to K^0\pi^0$:

$$d^q_{B^0_d\to K^0\pi^0} \;=\; \frac{1}{\sqrt{2}} h^q_{B^0_d\to K^+K^-} - h^q_{B^0_d\to\pi^0\pi^0}$$

$$|a^u_{K^0\pi^0}| \;\le\; \left|\frac{V_{us}}{V_{ud}}\right| \frac{\frac{1}{\sqrt{2}}\sqrt{\mathcal{B}(B\to K^+K^-)} + \sqrt{\mathcal{B}(B\to\pi^0\pi^0)}}{\sqrt{\mathcal{B}(B\to K^0\pi^0)}}$$

$$\Downarrow$$

$$\boxed{|a^u_{K\pi}| \le 0.15}$$

$\Longrightarrow\; [\Delta S_{\pi K_S}/\cos 2\beta]^2 + C^2_{\pi K_S} \le [0.30 \sin\gamma]^2$

hep-ph/0310020 (Gronau, Grossman, Rosner), hep-ph/0509125 (Raz)

Estimating $\Delta S_f \equiv -\eta_f S_f - S_{\psi K_S}$

$f_{\rm CP}$	EXP	NF*	QCDF**	SU(3)***
ϕK_S	-0.22 ± 0.19	$+0.02 \pm 0.01$	$+0.02 \pm 0.01$	$(K^* K)^\dagger$
$\eta' K_S$	-0.19 ± 0.09	$+0.01 \pm 0.02$	$+0.01 \pm 0.01$	0.31
$f_0 K_S$	$+0.06 \pm 0.24$			
$\pi^0 K_S$	-0.38 ± 0.26	$+0.06 \pm 0.04$	$+0.07 \pm 0.04$	0.18
ωK_S	-0.06 ± 0.30	$+0.19^{+0.06}_{-0.14}$	0.13 ± 0.08	$(K^* K)^\dagger$
$K_S K_S K_S$	-0.08 ± 0.23			1(0.37)
$K^+ K^- K_S^\ddagger$	-0.16 ± 0.17			0.94

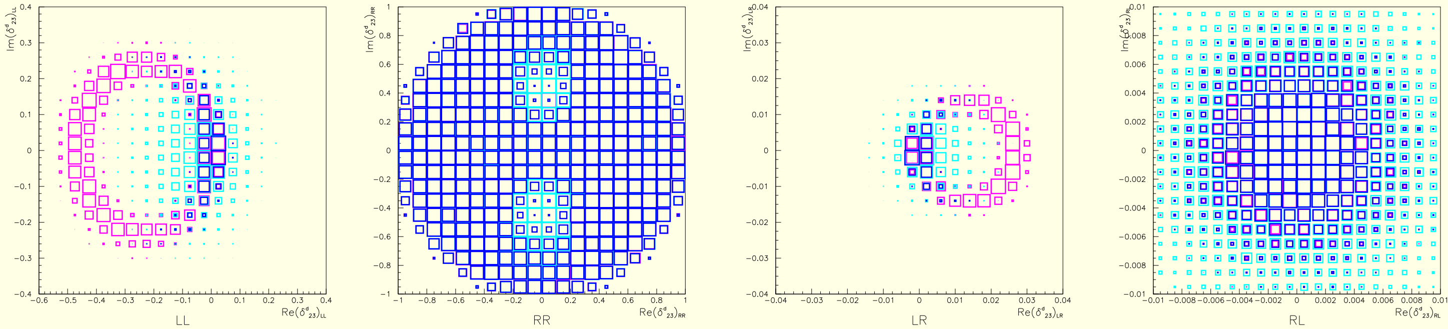
$*$ Buchalla, Hiller, Nir, Raz, hep-ph/0503151

$**$ Beneke, hep-ph/0505075

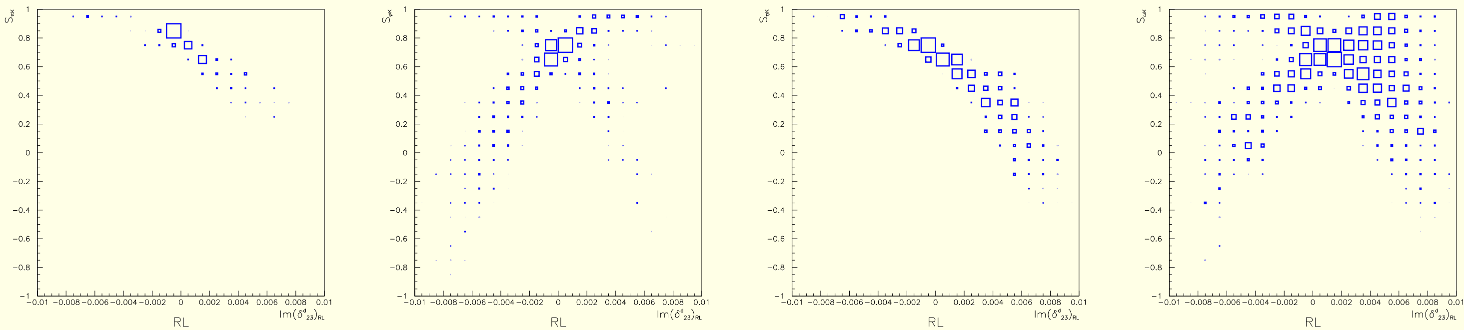
$***$ Grossman, Ligeti, Quinn, Nir, hep-ph/0303171; Raz *et al.*, hep-ph/0505195,0508046,0509125

† Available once $\mathcal{B}(K^* K)$ is measured

Supersymmetry: constraints and predictions



$(\delta^d_{23})_{LL}$ $(\delta^d_{23})_{RR}$ $(\delta^d_{23})_{LR}$ $(\delta^d_{23})_{RL}$



$S_{\pi K}$ $S_{\phi K}$ $S_{\eta' K}$ $S_{\omega K}$

Silvestrini, hep-ph/0510077

Supersymmetry: constraints and predictions

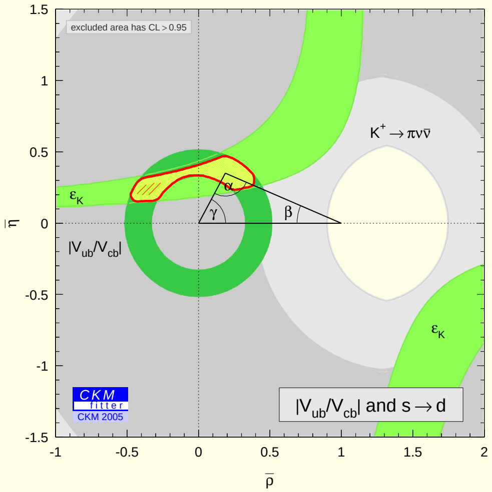
$(\delta^d_{23})_{MN}$	Upper Bound*	$\lvert\Delta S_{\phi K_S}\rvert \sim 0.1^{**}$	Alignment***
$(\delta^d_{23})_{LL}$	$\lambda^2(\mathcal{R}e) - \lambda(\mathcal{I}m)$	λ	λ^2
$(\delta^d_{23})_{RR}$	1	λ	$\lambda^4 - \lambda^2$
$(\delta^d_{23})_{LR}$	$\lambda^4(\mathcal{R}e) - \lambda^3(\mathcal{I}m)$	λ^4	$\lambda^2(m_b/\tilde{m})$
$(\delta^d_{23})_{RL}$	λ^3	λ^4	$\lambda^4(m_b/\tilde{m})$

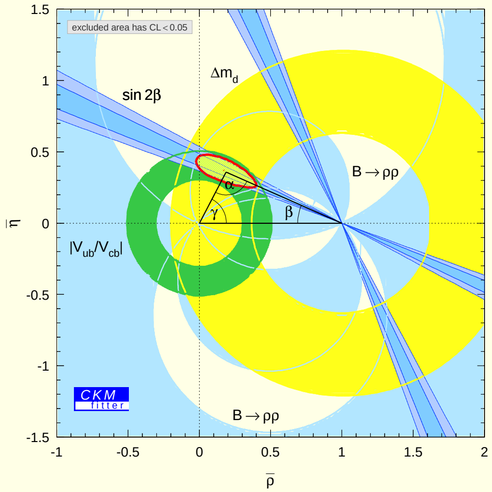
$*$ Ciuchini *et al.*, hep-ph/0407073

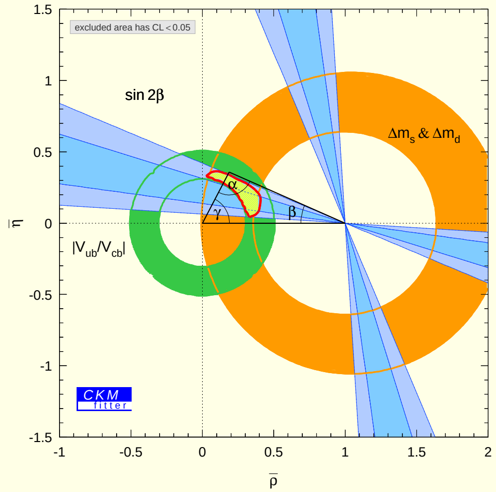
$**$ Silvestrini, hep-ph/0510077

$* * *$ Nir, Raz, hep-ph/0206064

Unitarity Triangles 2005







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

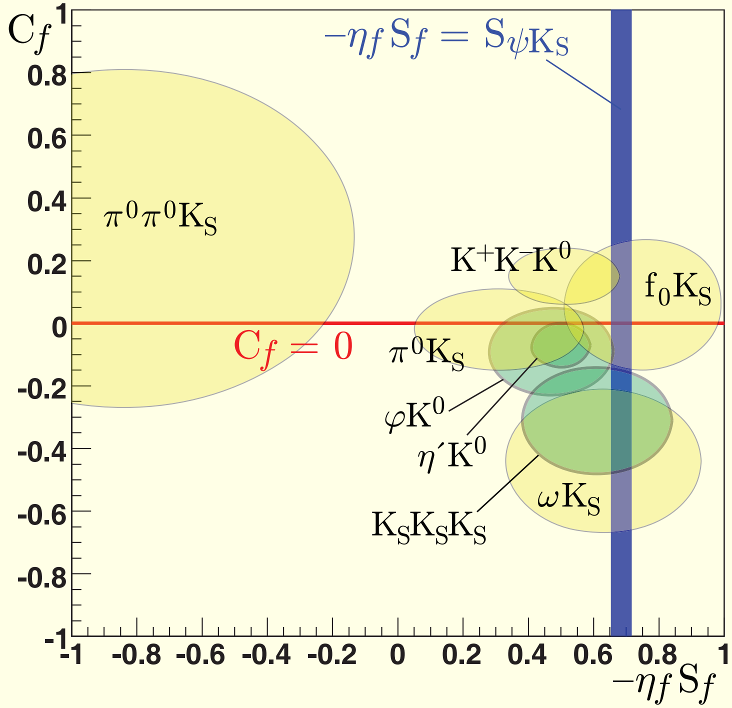
There is still a lot to be learned from future measurements

Höcker, T'Jampens, Laplace (05)

Conclusions

- The KM phase is different from zero (SM violates CP)
- The KM mechanism is, very likely, the dominant source of the CP violation observed in meson decays
- The size and the phase of NP contributions to $B^0 - \overline{B}^0$ mixing are severely constrained
- Complete alternatives to the KM mechanism are excluded (Superweak, Approximate CP)
- Corrections to KM are possible, particularly for $b \to s$;
  No evidence for such corrections at present
- There is still a lot to be learned from flavor/CP physics

Is there NP in $b \to s$ transitions?



Kirkby and Nir, PDG

No evidence at present

Experimental status of CP asymmetries

$f_{\rm CP}$	$-\eta_{\rm CP} S$	C
$\psi\pi^0$	$+0.69 \pm 0.25$	-0.11 ± 0.20
$D^+ D^-$	$+0.29 \pm 0.63$	$+0.11 \pm 0.35$
$D^{*+} D^{*-}$	$+0.75 \pm 0.23$	-0.04 ± 0.14
$\pi^+\pi^-$	$+0.50 \pm 0.12(0.18)$	$-0.37 \pm 0.10(0.23)$
$\pi^0\pi^0$		-0.28 ± 0.39
$\rho^+\rho^-$	$+0.22 \pm 0.22$	-0.02 ± 0.17

The NP CP/Flavor Problem

- $m_H^2 \sim (m_H^2)_{\rm tree} + \frac{1}{16\pi^2}\Lambda_{\rm NP}^2$
  To avoid fine-tuning of the Higgs mass,
  $\Lambda_{\rm NP} \lesssim 4\pi m_W \sim 1\ TeV$.

- $\mathcal{L}_{\rm NP} \sim \frac{1}{\Lambda_{\rm NP}^2} s\bar{d}s\bar{d}$
  To avoid too large contributions to ε_K and to $\Delta m_{K,D,B}$,
  $\Lambda_{\rm NP} \gtrsim 10^{3-4}\ TeV$.

New Physics at the TeV scale must have a very non-generic flavor and CP structure

SU(3) Relations

$$A_f = V_{cb}^* V_{cs} a_f^c + V_{ub}^* V_{us} a_f^u, \qquad \xi_f \equiv |V_{ub}V_{us}/V_{cb}V_{cs}|(a_f^c/a_f^u)$$

$$\boxed{-\eta_f S_f - S_{\psi K} = 2\cos 2\phi_1 \sin\phi_3 \, \mathcal{R}e(\xi_f)}$$

$$\boxed{C_f = -2\sin\phi_3 \, \mathcal{I}m(\xi_f)}$$

Grossman, Ligeti, Nir, Quinn (03)
Engelhard, Nir, Raz (05)

- Example: $|\xi_{\eta' K_S}| \leq \sqrt{\frac{3\mathcal{B}(\eta'\eta)}{2\mathcal{B}(\eta' K_S)}} + \sqrt{\frac{\mathcal{B}(\eta'\pi^0)}{2\mathcal{B}(\eta' K_S)}}$

mode	$\eta' K_S$	$\pi^0 K_S$	$K^-\pi^+$	$\eta' K^+$	ϕK^+	$K_S K_S K_S$
$\lvert\xi\rvert <$	0.25	0.18	0.23	0.07	0.22	$0.31^\dagger$

† Extra (mild) dynamical assumptions