CP Violation Beyond the Standard Model

5th Recontres du Vietnam
Hanoi – August 7, 2004

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Thanks to:

- Sandrine Laplace, Zoltan Ligeti

Why do theorists like CP violation?

1. The study of CPV is experiment-driven.

2. CP is a symmetry of the strong interactions*
   $\Longrightarrow$ Various CP asymmetries can be cleanly interpreted.

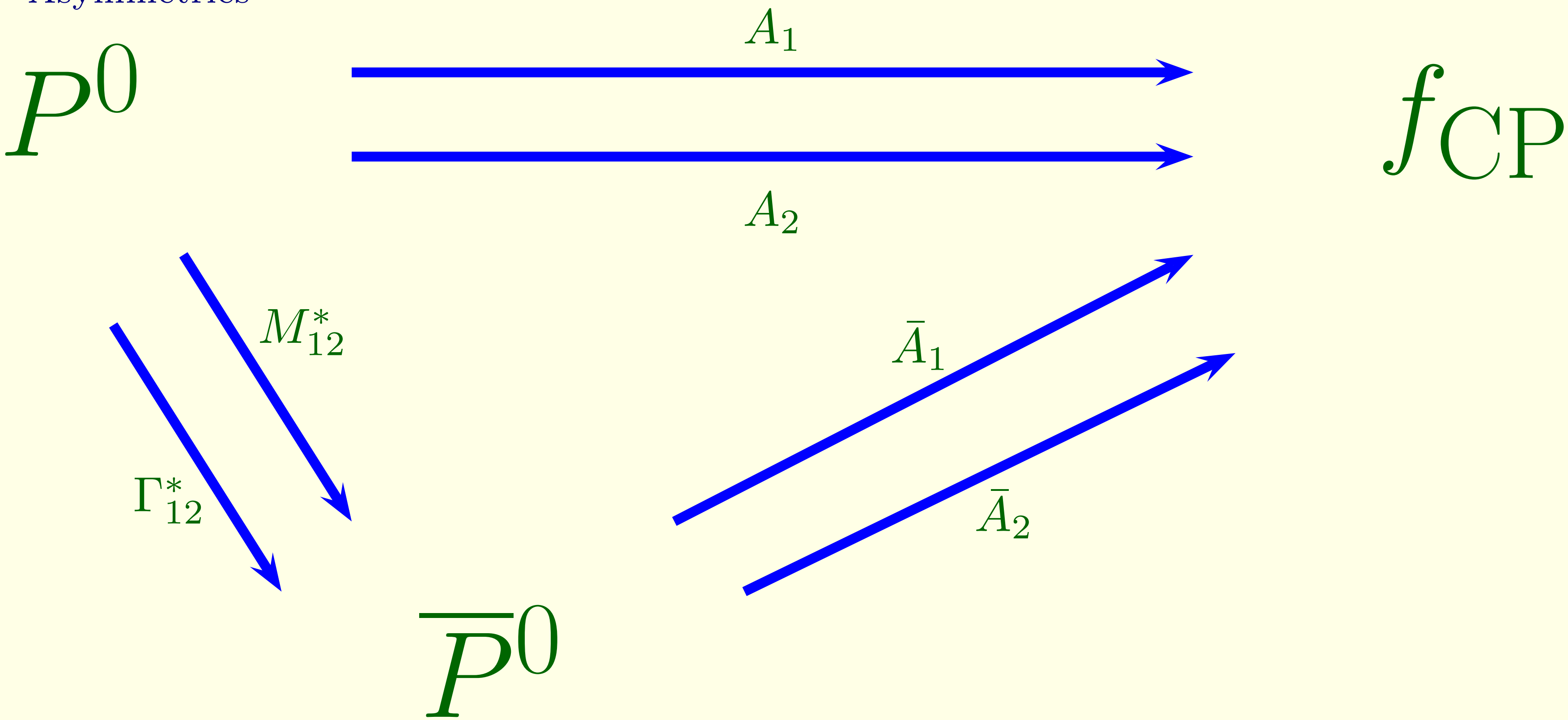
3. Almost any model of NP gives new sources of CPV;
   In particular, CPV probes the mechanism of supersymmetry breaking.

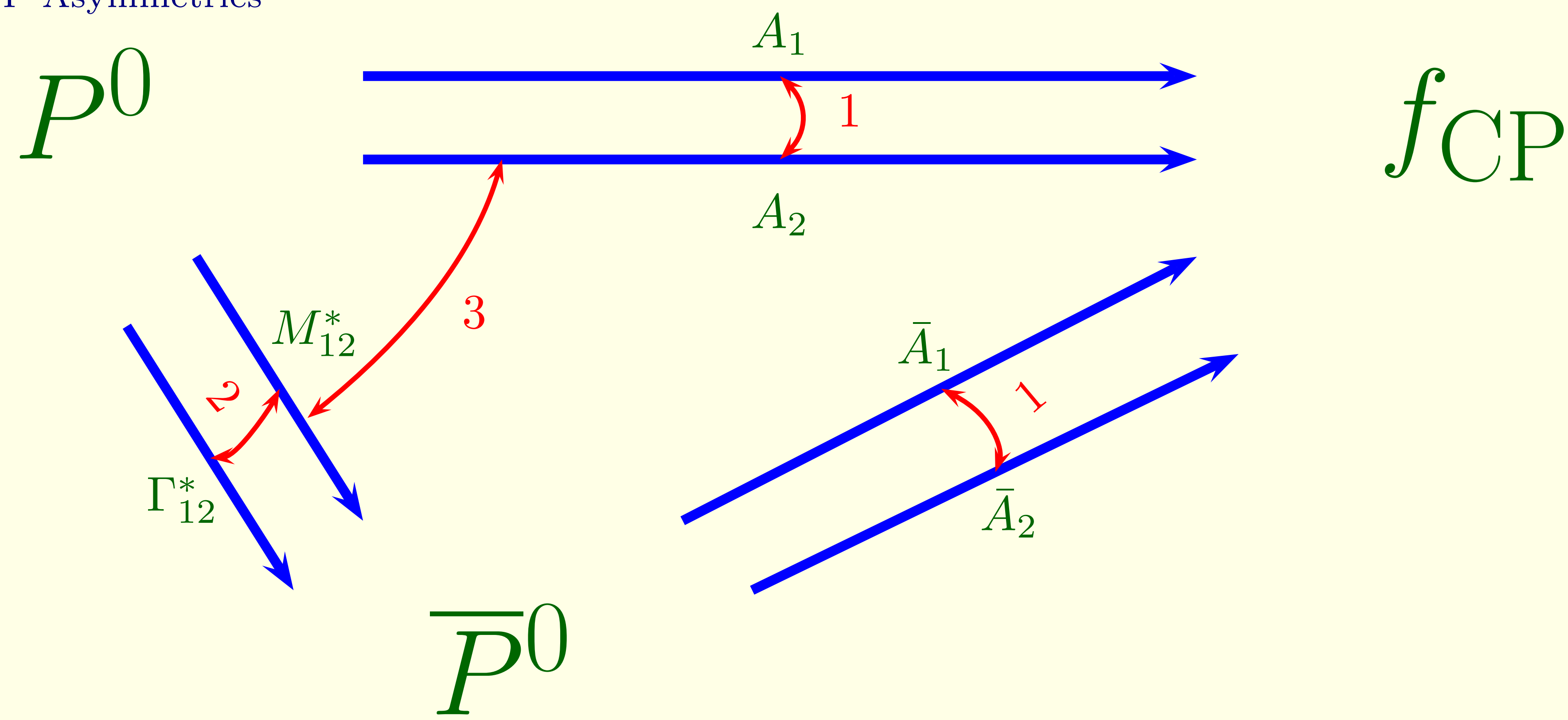
4. Baryogenesis implies that there must exist sources of CPV beyond the KM phase.

$*$ $\theta_{\rm QCD}$ is irrelevant in meson decays

Plan of Talk

1. CP asymmetries
2. $s \to u\bar{u}d$: $K \to \pi\pi$ (ε and ε')
3. $b \to c\bar{c}s$: $B \to \psi K$
4. $b \to s\bar{s}s$: $B \to \phi K,\ \eta' K,\ KKK$
5. Supersymmetry


P^0
A_1
A_2
f_{CP}
M_{12}^*
Γ_{12}^*
$\bar{A}_1$
$\bar{A}_2$
$\overline{P}^0$

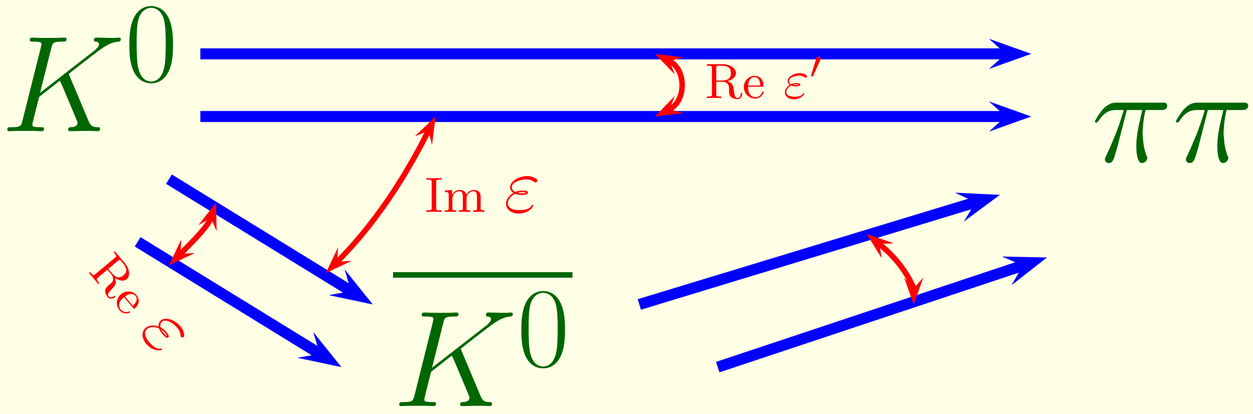


1	Decay	$\lvert\bar{A}/A\rvert \neq 1$	$\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}$	$\mathcal{R}e\ \varepsilon'$	$P^\pm \to f^\pm$
2	Mixing	$\lvert q/p\rvert \neq 1$	$\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta M - i\Delta\Gamma}$	$\mathcal{R}e\ \varepsilon$	$P^0, \overline{P}^0 \to \ell^\pm X$
3	Interference	$\mathcal{I}m\lambda \neq 0$	$\lambda = \frac{M_{12}^*}{\lvert M_{12}\rvert}\frac{\bar{A}}{A}$	$S_{\psi K_S}$	$P^0, \overline{P}^0 \to f_{\rm CP}$

Direct vs. Indirect CPV

- Indirect CPV
  - Can be accounted for by a phase in M_{12} only
  - $|q/p| \neq 1$ and/or a single $S_f \equiv \mathcal{I}m\lambda_f \neq 0$
  - Superweak models: only indirect CPV
- Direct CPV
  - cannot be accounted for by a phase in M_{12} only
  - $|\bar{A}/A| \neq 1$ and/or $S_{f_1} \neq S_{f_2}$
  - SM: possibly large direct CPV

$K \to \pi\pi$



$$|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3} \quad \left(\varepsilon = \frac{1-\lambda_0}{1+\lambda_0}\right)$$

Christenson, Cronin, Fitch, Turlay (64)

$$\mathcal{R}e\ \varepsilon'/\varepsilon = (1.67 \pm 0.26) \times 10^{-3} \quad \left(\varepsilon' = \frac{1}{6}(\lambda_{00} - \lambda_{+-})\right)$$

NA31 (88), KTeV (01), NA48 (02)

Lessons from ε

- CP violation has been observed.
- Old new physics: a third generation is required.
- A useful CKM constraint: the KM phase is large.
- The NP CP/flavor problem.

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,
  $\Lambda_{\rm NP} \lesssim 4\pi m_W \sim 1\ TeV$.

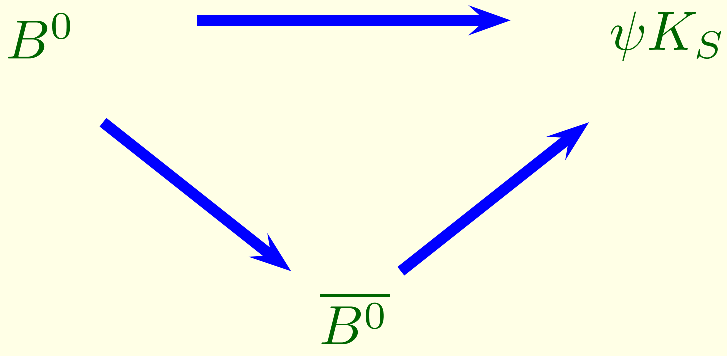
- $\mathcal{L}_{\rm NP} \sim \frac{1}{\Lambda_{\rm NP}^2} s\bar{d}s\bar{d}$
  To avoid too large contributions to ε_K and to $\Delta m_{K,D,B}$,
  $\Lambda_{\rm NP} \gtrsim 10^{3-4}\ TeV$.

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

Lessons from ε'/ε

- Direct CP violation has been observed.
- The result is consistent with the SM predictions.
- Large hadronic uncertainties $\Longrightarrow$ no useful CKM constraint.
- The superweak scenario is excluded. Wolfenstein (64)
- New physics (*e.g.* Supersymmetry) may contribute significantly. e.g. Masiero and Murayama (99)

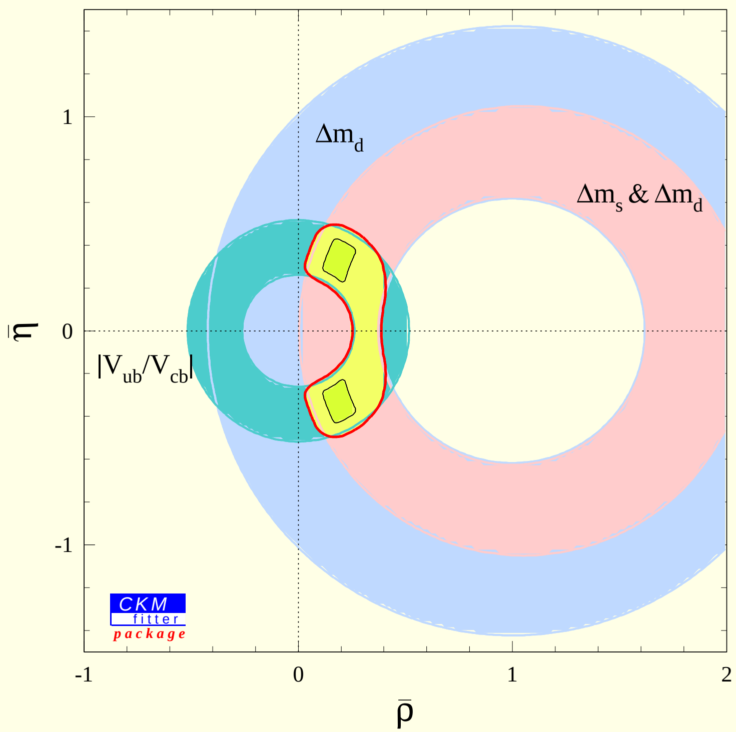
Carter and Sanda (80)
Bigi and Sanda (81)



- Within SM, dominated by a single phase $\Longrightarrow$ $\boxed{C_{\psi K_S} = 0}$
  (Subleading phase 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	CP	$S_{\psi K_S}$	$C_{\psi K_S}$
ψK_S	$-$	$+0.74 \pm 0.05$	0.02 ± 0.04

Unitarity Triangles



Tree level + CPC observables

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

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

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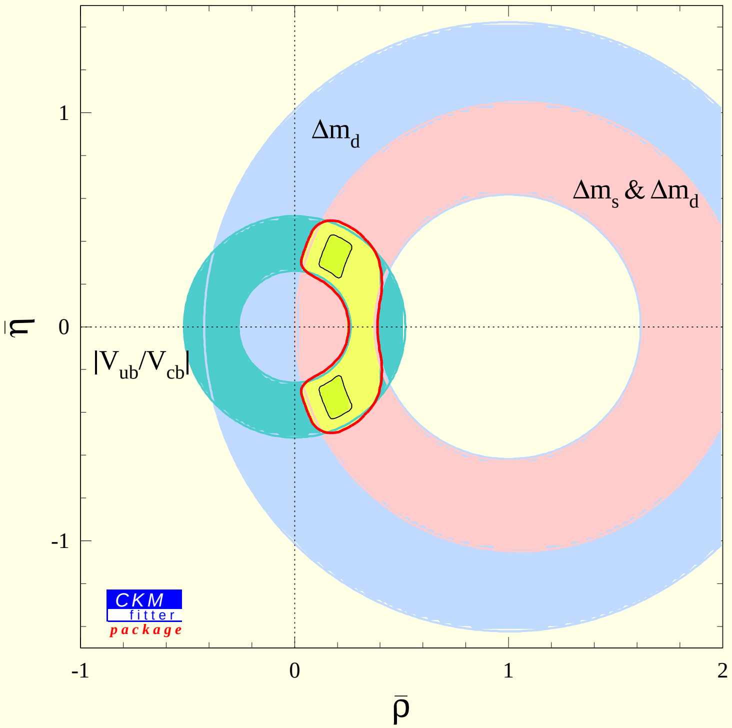

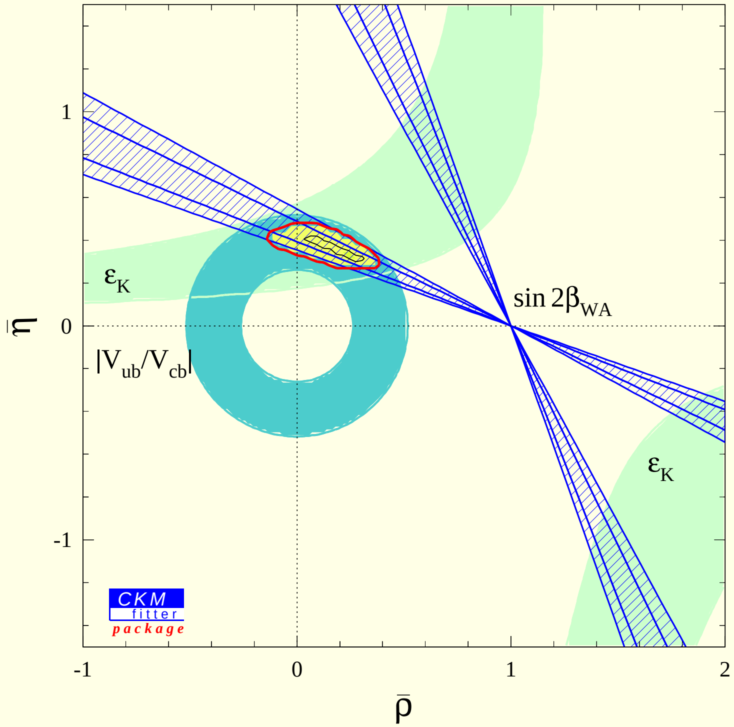

Tree level + CPC observables

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

Tree level + CPV observables

$\varepsilon, \quad S_{\psi K_S}$

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

Lessons from $S_{\psi K}$

- 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 $(\bar{\rho}, \bar{\eta})$:

$$\boxed{\mathcal{I}m\lambda_{\psi K_S} = \sin 2\beta = \frac{2\bar{\eta}(1-\bar{\rho})}{\bar{\eta}^2+(1-\bar{\rho})^2} = 0.74 \pm 0.05}$$

- 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.

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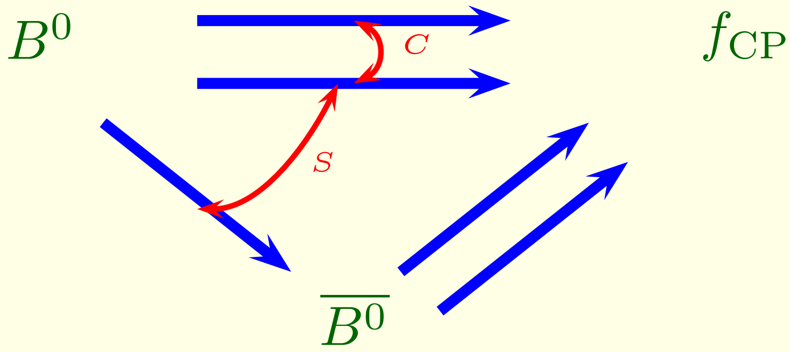
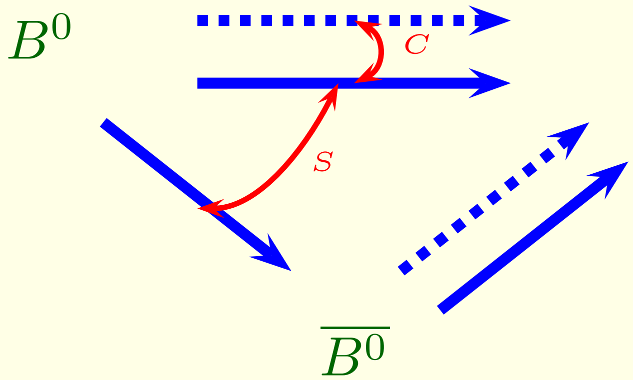
  Very likely, the KM mechanism is the dominant source of CP violation in flavor changing processes

  - '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.



$f_{\rm CP}$	$b \to q\bar{q}q'$	SM	$-\eta_{\rm CP} S = \pm \frac{2\mathcal{I}m\lambda}{1+\lvert\lambda\rvert^2}$	$C = \frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}$
ψK_S	$b \to c\bar{c}s$	$\sin 2\beta$	$+0.74 \pm 0.05$	$+0.02 \pm 0.04$
ϕK_S	$b \to s\bar{s}s$	$\sin 2\beta$	$+0.02 \pm 0.67$	$+0.09 \pm 0.23$
$\eta' K_S$	$b \to s\bar{s}s$	$\sin 2\beta$	$+0.27 \pm 0.21$	$+0.04 \pm 0.13$
$K^+K^-K_S$	$b \to s\bar{s}s$	$\sin 2\beta$	$+0.54 \pm 0.18$	$+0.07 \pm 0.13$
$\pi^0 K_S$	$b \to u\bar{u}s$	$\sin 2\beta_{\rm eff}$	$+0.48 \pm 0.40$	$+0.40 \pm 0.30$
$D^{*+}D^{*-}$	$b \to c\bar{c}d$	$\sin 2\beta_{\rm eff}$	-0.05 ± 0.31	$+0.25 \pm 0.19$
$\psi\pi^0$	$b \to c\bar{c}d$	$\sin 2\beta_{\rm eff}$	$+0.43 \pm 0.38$	$+0.13 \pm 0.24$
$\pi^+\pi^-$	$b \to u\bar{u}d$	$\sin 2\alpha_{\rm eff}$	$+0.70 \pm 0.31$	-0.42 ± 0.20
$\rho^+\rho^-$	$b \to u\bar{u}d$	$\sin 2\alpha_{\rm eff}$	$+0.42 \pm 0.44$	-0.17 ± 0.30



$\phi K_S, \eta' K_S, KKK$

- Within SM, dominated by a single phase $\Longrightarrow$ $\boxed{C \approx 0}$ (Subleading phase CKM-suppressed)
- Within SM, $A \propto V_{cb}^* V_{cd}$ $\Longrightarrow$ $\boxed{S \approx S_{\psi K_S} (\approx +0.74)}$
- With NP, $S \neq S_{\psi K_S}$, $S_{f_1} \neq S_{f_2}$ and $C \neq 0$ are possible.

mode	CP	$-\eta_{\rm CP} S$	C
ϕK_S	$-$	$+0.02 \pm 0.29 (0.67)^\dagger$	$+0.09 \pm 0.23$
$\eta' K_S$	$-$	$+0.27 \pm 0.21$	$+0.04 \pm 0.13$
$K^+ K^- K_S$	$+^*$	$+0.54 \pm 0.18$	$+0.07 \pm 0.13$

† Babar: $+0.47 \pm 0.34 \pm 0.07$; Belle: $-0.96 \pm 0.50 \pm 0.10$

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

A SM CP/Flavor Problem?

- CP asymmetries in $b \to s\bar{s}s$: $S_{\eta' K_S}, \quad S_{\phi K_S}$
- Polarization in $B \to \phi K^*$: $f_\sigma \equiv \frac{|A_\sigma|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$
  - Theoretically (HQE),
    $(f_\parallel + f_\perp)/f_0 = \mathcal{O}(1/m_B^2), \quad f_\perp/f_\parallel = 1 + \mathcal{O}(1/m_B)$.
  - Experimentally, $f_0(\rho^0 K^{*+}) = 0.96 \pm 0.16$,
    $f_0(\rho^0\rho^+) = 0.96 \pm 0.07$, $f_0(\rho^+\rho^-) = 0.99 \pm 0.08$
    but $f_0(\phi K^{*0}) = 0.58 \pm 0.10$, $f_\perp(\phi K^{*0}) = 0.41 \pm 0.11$,
    $f_0(\phi K^{*+}) = 0.46 \pm 0.12$.
- The lipkin sum rule: $R_L \equiv 2\frac{\Gamma(B^+\to K^+\pi^0)+\Gamma(B^0\to K^0\pi^0)}{\Gamma(B^+\to K^0\pi^+)+\Gamma(B^0\to K^+\pi^-)}$
  - Theoretically (isospin),
    $R_L = 1 + \mathcal{O}\left(\frac{P_{\rm EW}+T}{P}\right)^2 = 1 + \mathcal{O}(10^{-2})$
  - Experimentally, $R_L = 1.24 \pm 0.10$.

A SM CP/Flavor Problem – Not Yet...

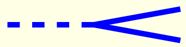
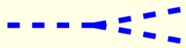
- $S_{\eta' K_S} = 0.27 \pm 0.21$:
  $\sim 2\sigma$.

- $S_{\phi K_S} = +0.02 \pm 0.67$:
  Experimental situation needs to be resolved.

- $f_0(\phi K^{*0}) = 0.58 \pm 0.10, \quad f_\perp(\phi K^{*0}) = 0.41 \pm 0.11$:
  Charming penguins (SCET) / Annihilation diagrams (QCDF) can account for the data.

- $R_L = 1.24 \pm 0.10$:
  $\sim 2.4\sigma$
  More theoretical effort is needed to determine T/P

Supersymmetry for Phenomenologists

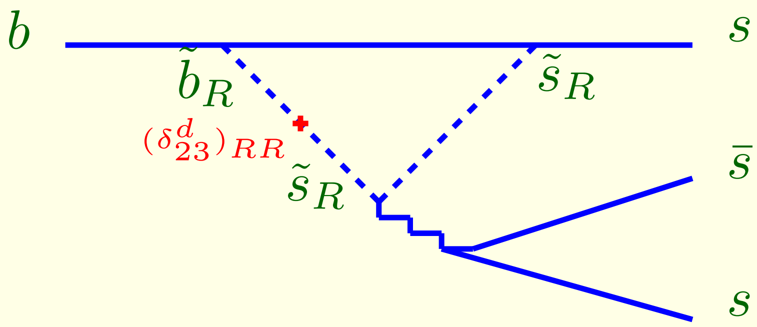
		FV	CPV
	Y	$+$	$+$
	μ	$-$	$+$
	A	$+$	$+$
	$m_{\tilde{g}}$	$-$	$+$
	$m^2_{\tilde{f}}$	$+$	$+$
	B	$-$	$+$

80 real + 44 imaginary parameters

CP Violation in Supersymmetry

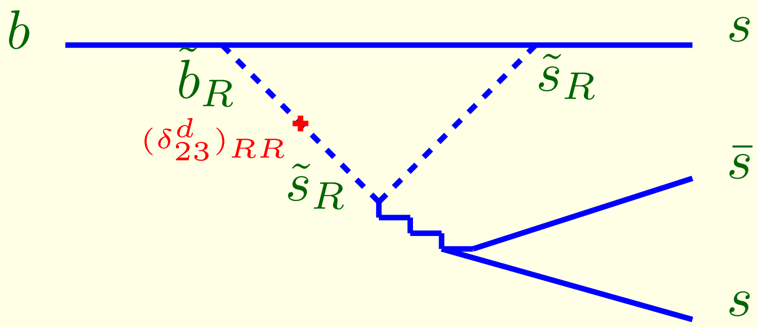
- K physics: $\frac{\mathcal{I}m M_{12}^{\rm SUSY}}{\mathcal{I}m M_{12}^{\rm exp}} \sim 10^6 \left(\frac{1\ TeV}{\tilde{m}}\right)^2 \left(\frac{\Delta\tilde{m}_{12}^2}{\tilde{m}^2}\right)^2 \mathcal{I}m\left[(K_{12}^d)^2\right]$
  - Heavy squarks: $\tilde{m} > 1\ TeV$;
  - Universality: $\Delta\tilde{m}_{21}^2 \ll \tilde{m}^2$;
  - Alignment: $|K_{12}^d| \ll 1$;
  - (Approximate CP: $\sin\phi \ll 1$)
- B physics: $S_{\psi K}^{\rm exp} \simeq S_{\psi K}^{\rm SM}$
  - consistent with exact universality,
  - constrains U(2) and U(1) models, disfavors heavy squarks.
- D physics: $x, y \lesssim 0.05$
  - probes alignment.
- EDMs: $\frac{d_N^{\rm SUSY}}{6.3\times10^{-26}\ e\ {\rm cm}} \sim 300 \left(\frac{100\ GeV}{\tilde{m}}\right)^2 \sin\phi_{A,B}$
  - can distinguish MFV ($\lesssim 10^{-31}$) from SUSY CPV ($\gtrsim 10^{-28}$).

SUSY contributions to $B \to \phi K_S$



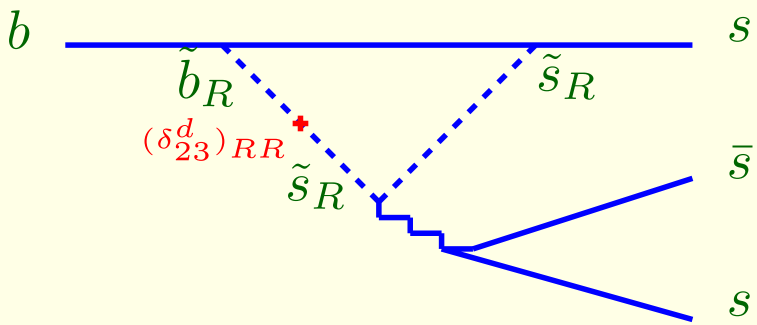
- Could there be large effects in $B \to \phi K_S$ and not in $B \to \psi K_S$?

SUSY contributions to $B \to \phi K_S$



- Could there be large effects in $B \to \phi K_S$ and not in $B \to \psi K_S$?
  - Yes: $\delta^d_{23} \leftrightarrow \delta^d_{13}$
- Could there be large effects in $B \to \phi K_S$ and not in $B \to X_s \gamma$?

SUSY contributions to $B \to \phi K_S$



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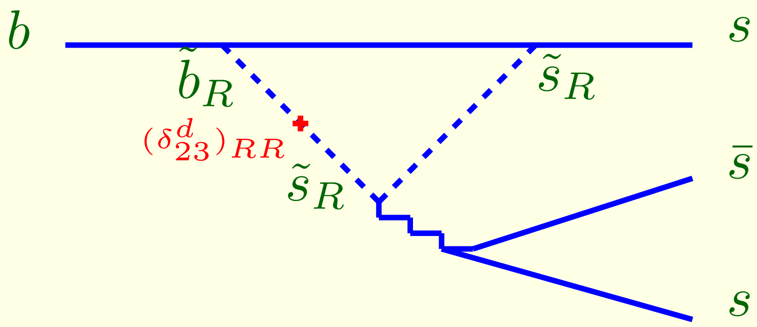
  - Yes: $\delta^d_{23} \leftrightarrow \delta^d_{13}$
- Could there be large effects in $B \to \phi K_S$ and not in $B \to X_s \gamma$?
  - Yes: $\delta^d_{RR} \leftrightarrow \delta^d_{LR}$
- Are there well-motivated models with $(\delta^d_{23})_{RR} = \mathcal{O}(1)$?

SUSY contributions to $B \to \phi K_S$



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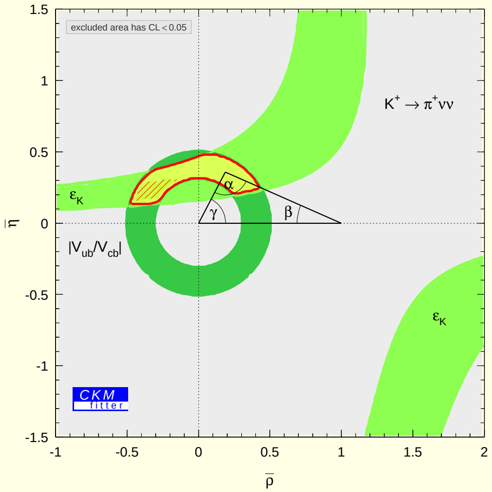
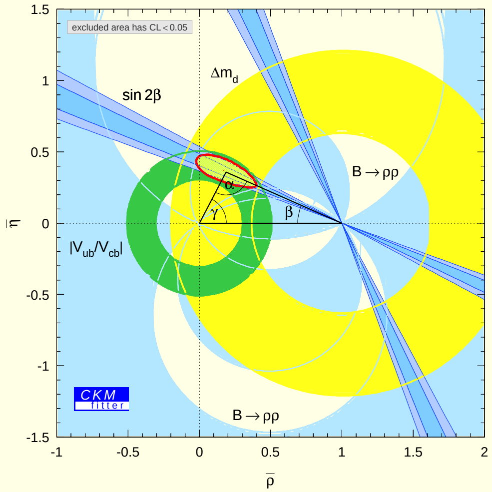
- Could there be large effects in $B \to \phi K_S$ and not in $B \to X_s \gamma$?
  - Yes: $\delta^d_{RR} \leftrightarrow \delta^d_{LR}$
- Are there well-motivated models with $(\delta^d_{23})_{RR} = \mathcal{O}(1)$?
  - U(1) flavor symmetry: $(\delta^d_{23})_{RR} \sim (m_s/m_b)/|V_{cb}|$
  - SO(10) GUTs: $(\delta^d_{23})_{RR} \sim \theta^\ell_{23}$

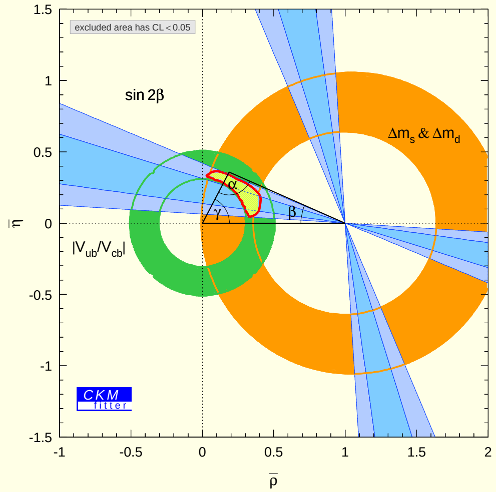
Conclusions

- The KM mechanism is, very likely, the dominant source of the CP violation observed in meson decays
- CPV observed ($\geq 3\sigma$ from Babar+Belle) in three modes:
  $S_{\psi K_S} = 0.74 \pm 0.05$, $S_{K^+K^-K_S} = -0.54 \pm 0.18$,
  $\mathcal{A}_{K^\mp\pi^\pm} = -0.114 \pm 0.024$ (direct CPV!)
- No evidence for new flavor/CP physics
  - $\sim 2\sigma$ effect in $S_{\eta' K_S}$
  - "$\sim 2.5\sigma$" effect in $S_{D^{*+}D^{*-}}$
- We left the era of hoping for NP altenratives to KM;
  We are in the era of seeking for NP corrections to KM
- The field is experiment-driven
  Waiting for new results from Belle/Babar/TeVatron

Unitarity Triangles 2004





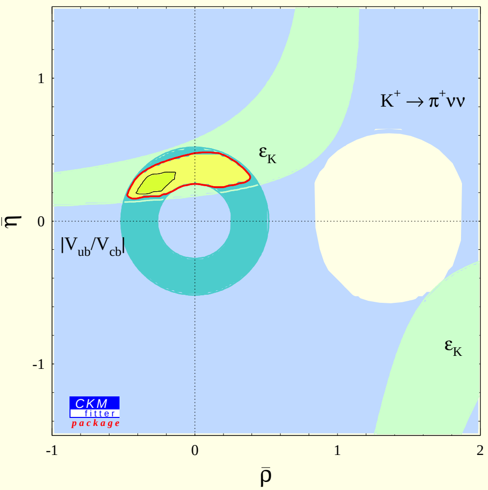


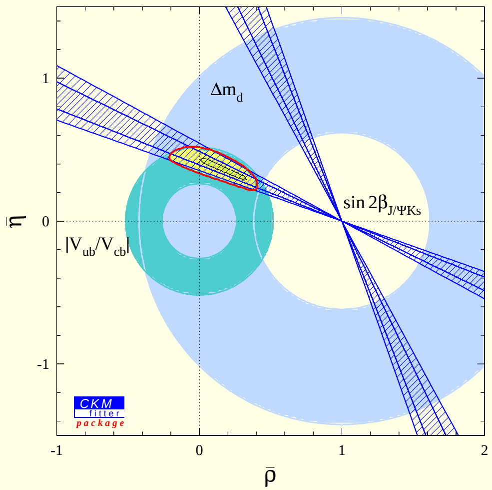
$s \to d$	$b \to d$	$b \to s$
$\varepsilon,\ \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$\Delta m_{B_d},\ S_{\psi K},\ S_{\rho\rho}$	$\Delta m_{B_s},\ S_{\phi K,\eta' K, KKK}$

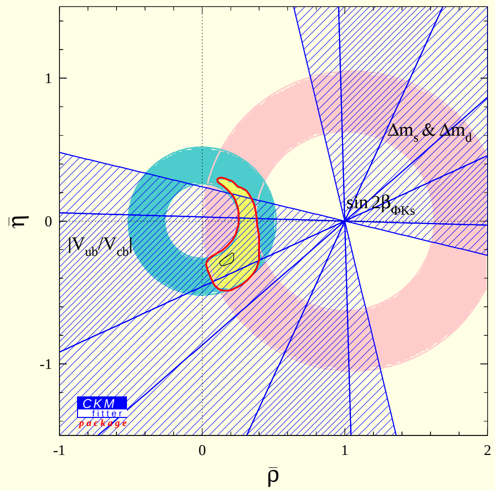
There is still a lot to be learnt from future measurements

Laplace (04)

Unitarity Triangles 2002





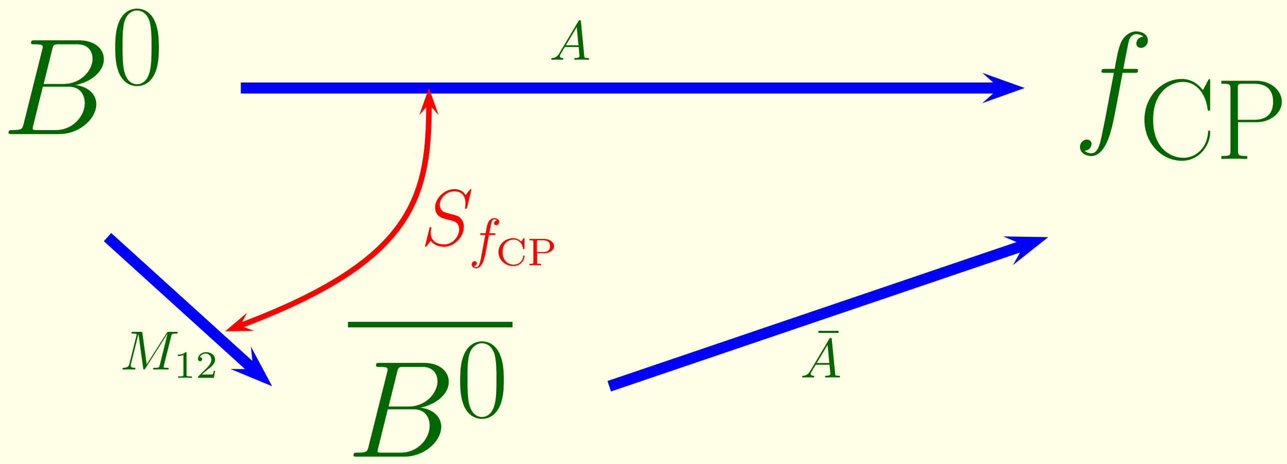


$s \to d$	$b \to d$	$b \to s$
$\varepsilon, \quad \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$\Delta m_{B_d}, \quad S_{\psi K_S}$	$\Delta m_{B_s}, \quad S_{\phi K_S}$

There is still a lot to be learnt from future measurements

Laplace (02)

The case theorists love



1. Decay dominated by a single CPV phase: $|\bar{A}/A| = 1$
2. CPV in mixing negligible: $|q/p| = 1$
3. The only remaining effect is
   $\mathcal{A}_{f_{\rm CP}}(t) = S_{f_{\rm CP}} \sin(\Delta m_B\ t)$

$$\boxed{S_{f_{\rm CP}} = \mathcal{I}m \lambda_{f_{\rm CP}} = \pm \sin[\arg(M_{12}^*) + \arg(\bar{A}_{f_{\rm CP}}) - \arg(A_{f_{\rm CP}})]}$$