CP Violation

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Acknowledgments:

- Adam Falk *(JHU)*
- Yuval Grossman *(Technion)*
- Sandrine Laplace *(Orsay)*
- Zoltan Ligeti *(LBL)*
- Guy Raz *(WIS)*

Why do theorists like CP violation?

1. At last, 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 new physics gives new sources of CPV.

4. CPV probes the mechanism of dynamical SUSY breaking.

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

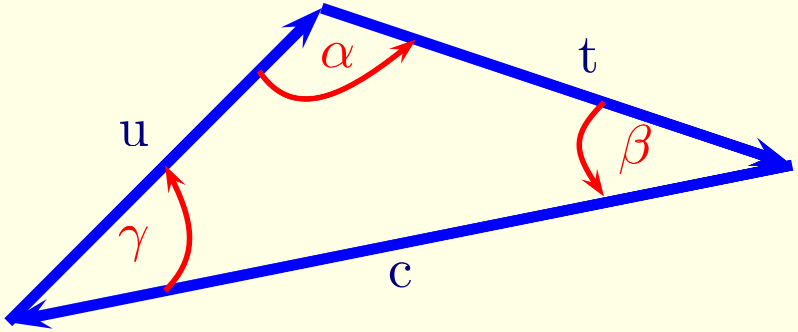
Plan of Talk

1. The CKM matrix
   - (a) CPC vs CPV
   - (b) B vs K
2. Results and Basic Implications
   - (a) K physics
   - (b) B physics
3. Supersymmetry (SUSY)
4. Conclusions

In case that the UT was not shown before...

- A geometrical presentation of $\boxed{V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cd}^* V_{cb} = 0}$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



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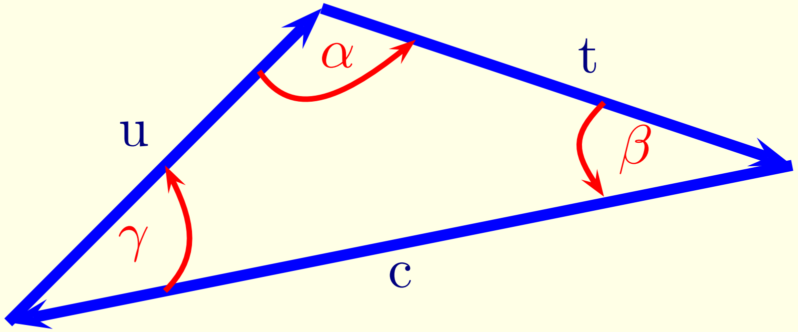
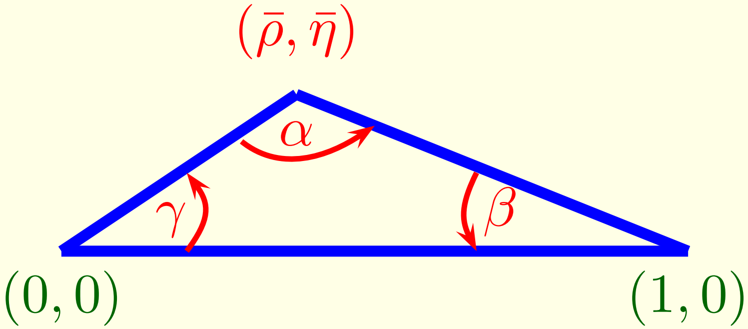


- Rescale and rotate: $\boxed{A\lambda^3 \left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)\right] = 0}$

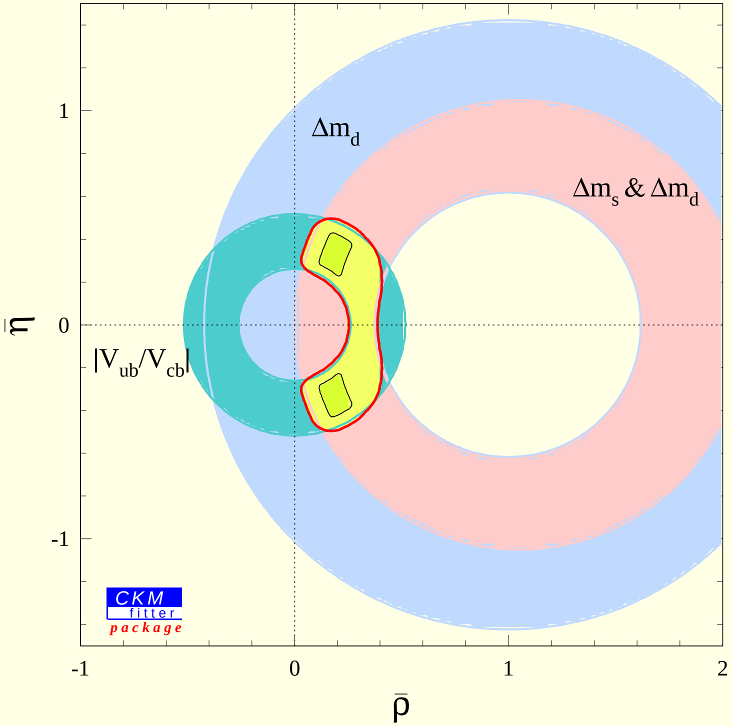
$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Wolfenstein (83); Buras *et al.* (94)

$\alpha \equiv \phi_2; \quad \beta \equiv \phi_1; \quad \gamma \equiv \phi_3$

Unitarity Triangles

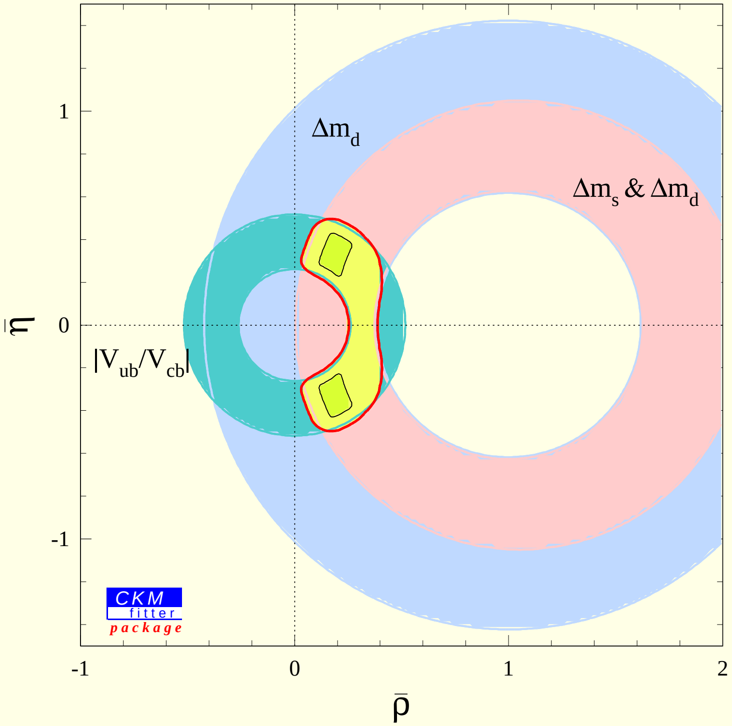


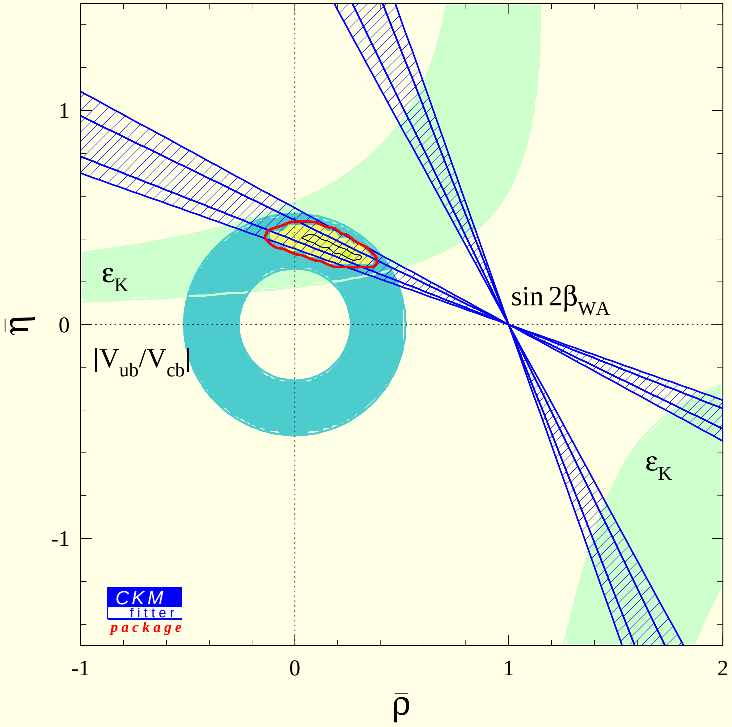
Tree level + CPC observables

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

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

Unitarity Triangles





Tree level + CPC observables

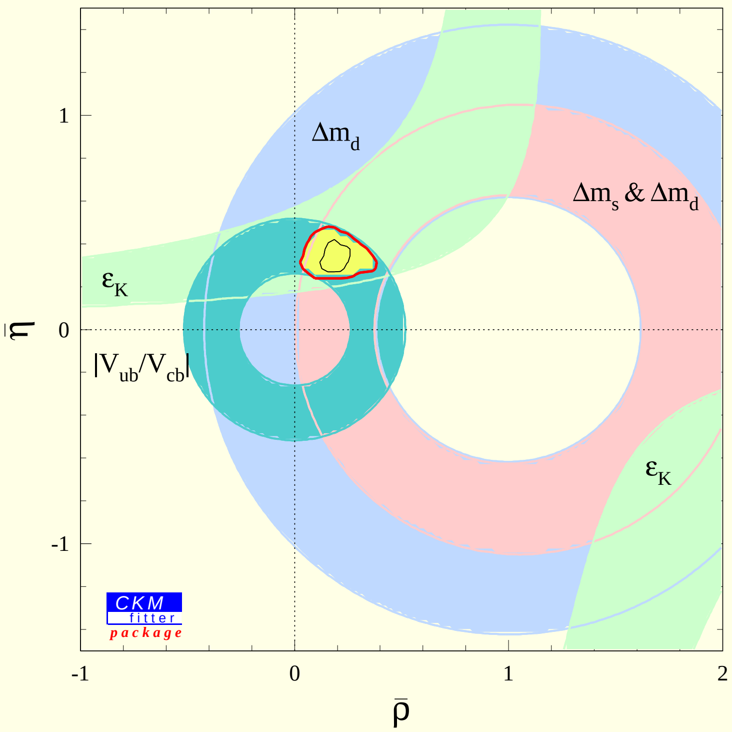
$\Delta m_B, \quad \Delta m_{B_s}$

Tree level + CPV observables

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

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

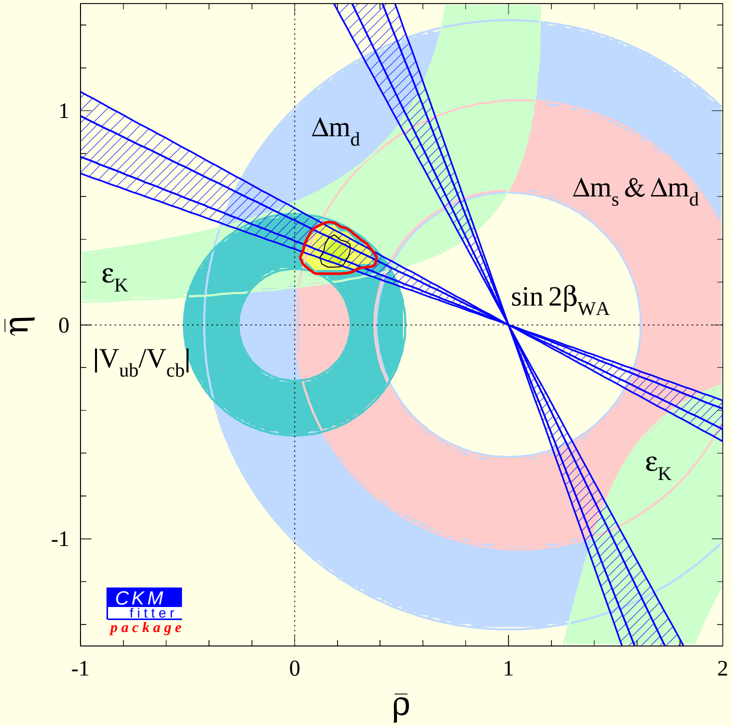
Unitarity Triangles



Without $S_{\psi K}$

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

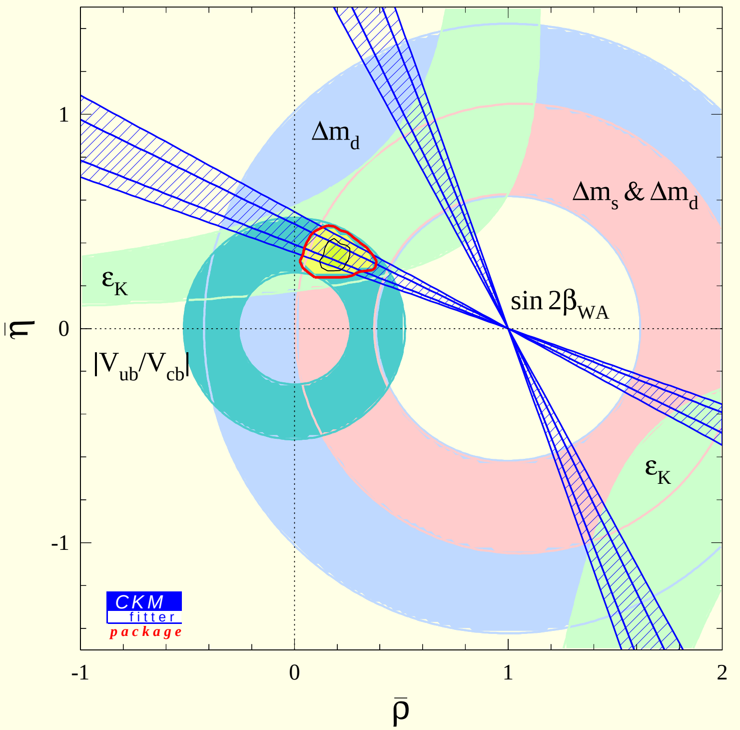
Unitarity Triangles



Without $S_{\psi K}$

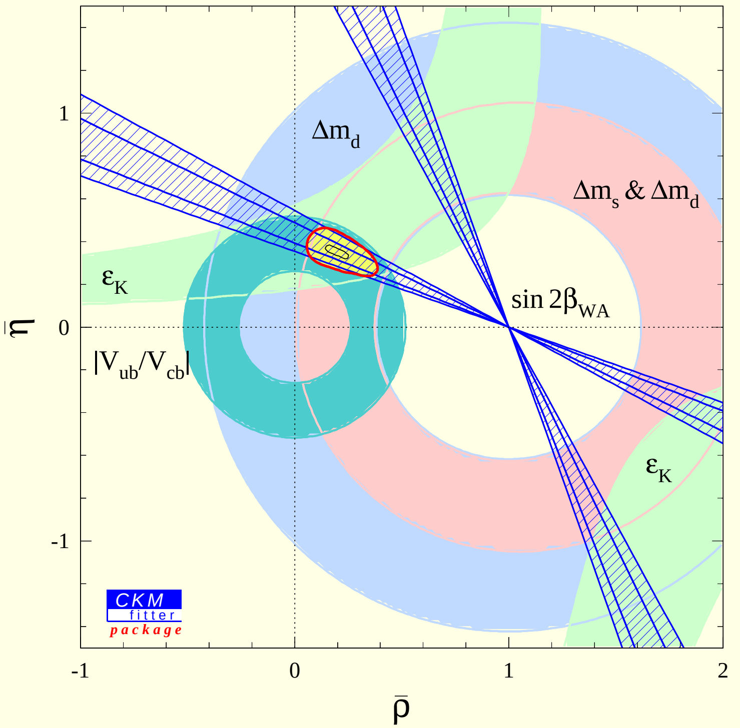
$\Delta m_B, \;\; \Delta m_{B_s}, \;\; \varepsilon$

Unitarity Triangles



Without $S_{\psi K}$

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



With $S_{\psi K}$

$\Delta m_B, \;\; \Delta m_{B_s}, \;\; \varepsilon, \;\; S_{\psi K_S}$

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

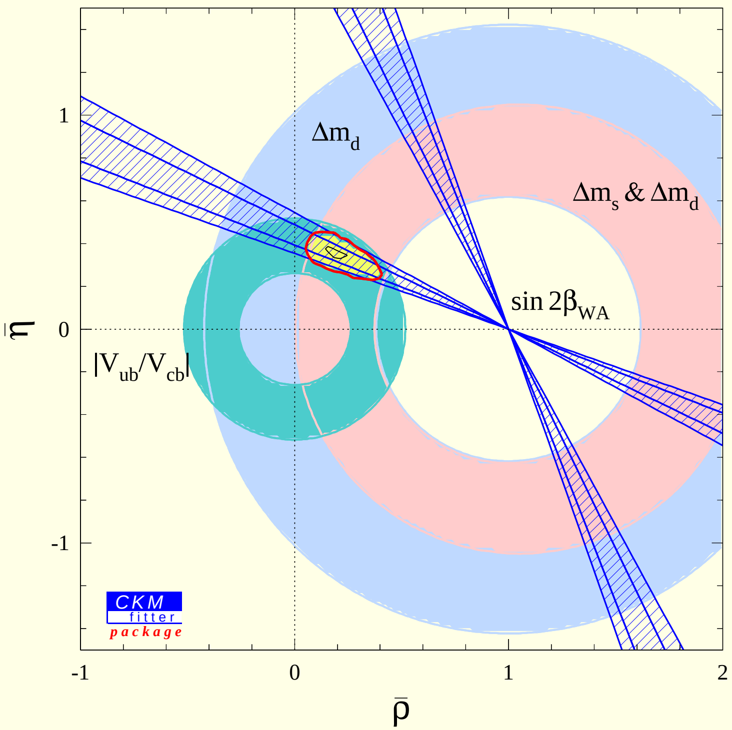
The KM mechanism

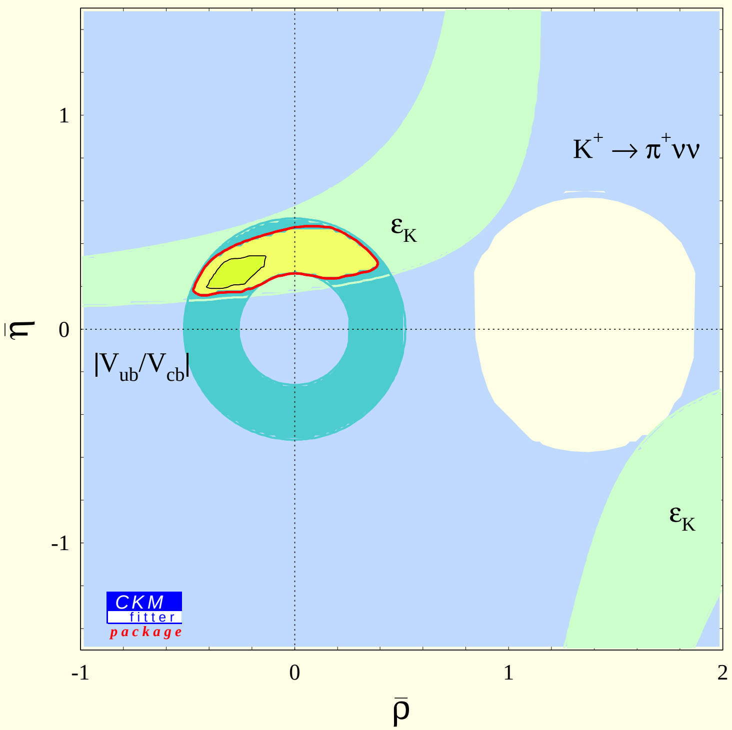
- The KM mechanism successfully passed its first precision test

$$\boxed{\text{Very likely, the KM mechanism is the dominant source of CP violation in flavor changing processes}}$$

- '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.

Unitarity Triangles





Tree level + *B* physics

$\Delta m_B, \quad \Delta m_{B_s}, \quad S_{\psi K}$

Tree level + *K* physics

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

FCNC $B-$ and $K-$Decays

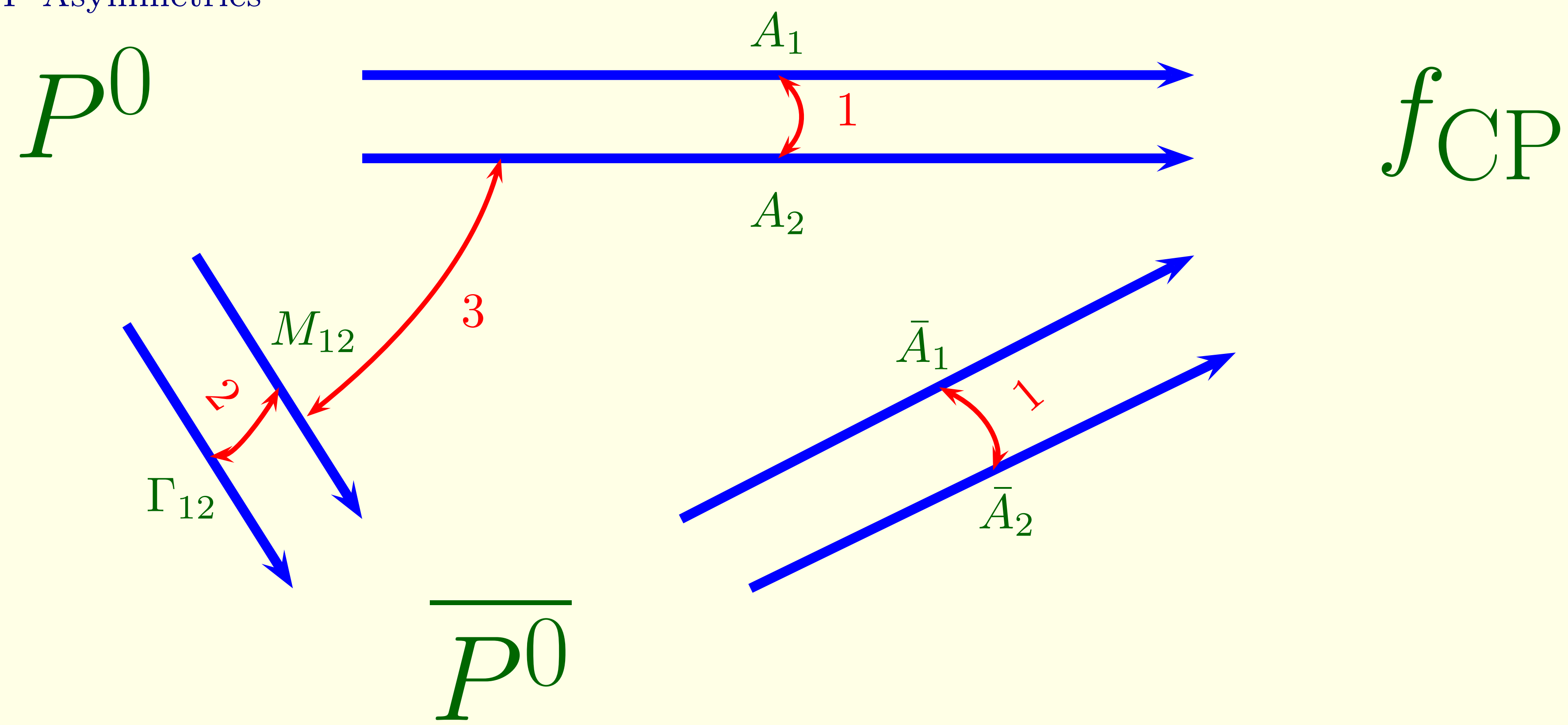
- There is no sign of new flavor physics.

- At present, the data from B physics provide much stronger constraints on the $(\bar{\rho}, \bar{\eta})$ parameters.

- Measurements of $K \to \pi \nu \bar{\nu}$ decays can lead to similar accuracy from K physics.

CP Asymmetries

$$\begin{tikzcd}
P^0 \arrow[rr, shift left, "A_1"] \arrow[rr, shift right, "A_2"'] \arrow[dr, shift left, "M_{12}"] \arrow[dr, shift right, "\Gamma_{12}"'] & & f_{\mathrm{CP}} \\
& \overline{P^0} \arrow[ur, shift left, "\bar{A}_1"] \arrow[ur, shift right, "\bar{A}_2"'] &
\end{tikzcd}$$



1. In decay: $|\bar{A}/A| \neq 1$ $\left(\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}\right)$
2. In mixing: $|q/p| \neq 1$ $\left(\frac{q}{p} = \frac{2M_{12}^*-i\Gamma_{12}^*}{\Delta m-(i/2)\Delta\Gamma}\right)$
3. In interference: $\mathcal{I}m\lambda \neq 0$ $\left(\lambda = \frac{q}{p}\frac{\bar{A}}{A}\right)$

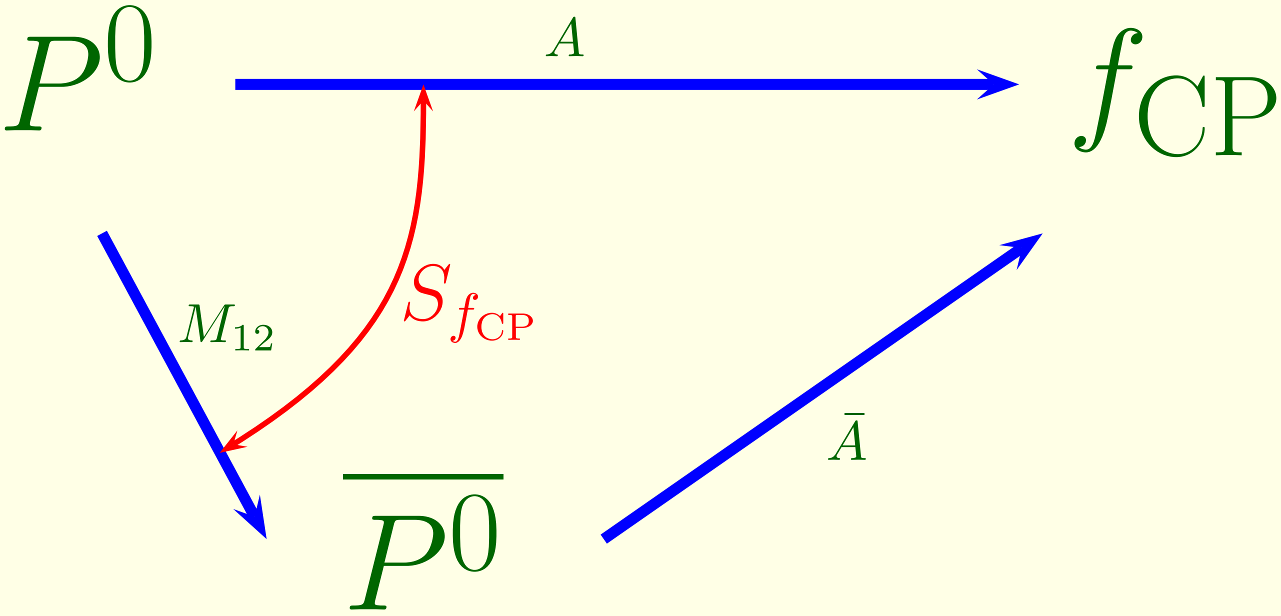
Types of CP Asymmetries

$$\mathcal{A}_{f^\mp} \equiv \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)} = \frac{|\bar{A}_f/A_f|^2 - 1}{|\bar{A}_f/A_f|^2 + 1}$$

$$\mathcal{A}_{\rm SL} \equiv \frac{\Gamma(\bar{B}^0_{\rm phys}(t) \to \ell^+ X) - \Gamma(B^0_{\rm phys}(t) \to \ell^- X)}{\Gamma(\bar{B}^0_{\rm phys}(t) \to \ell^+ X) + \Gamma(B^0_{\rm phys}(t) \to \ell^- X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

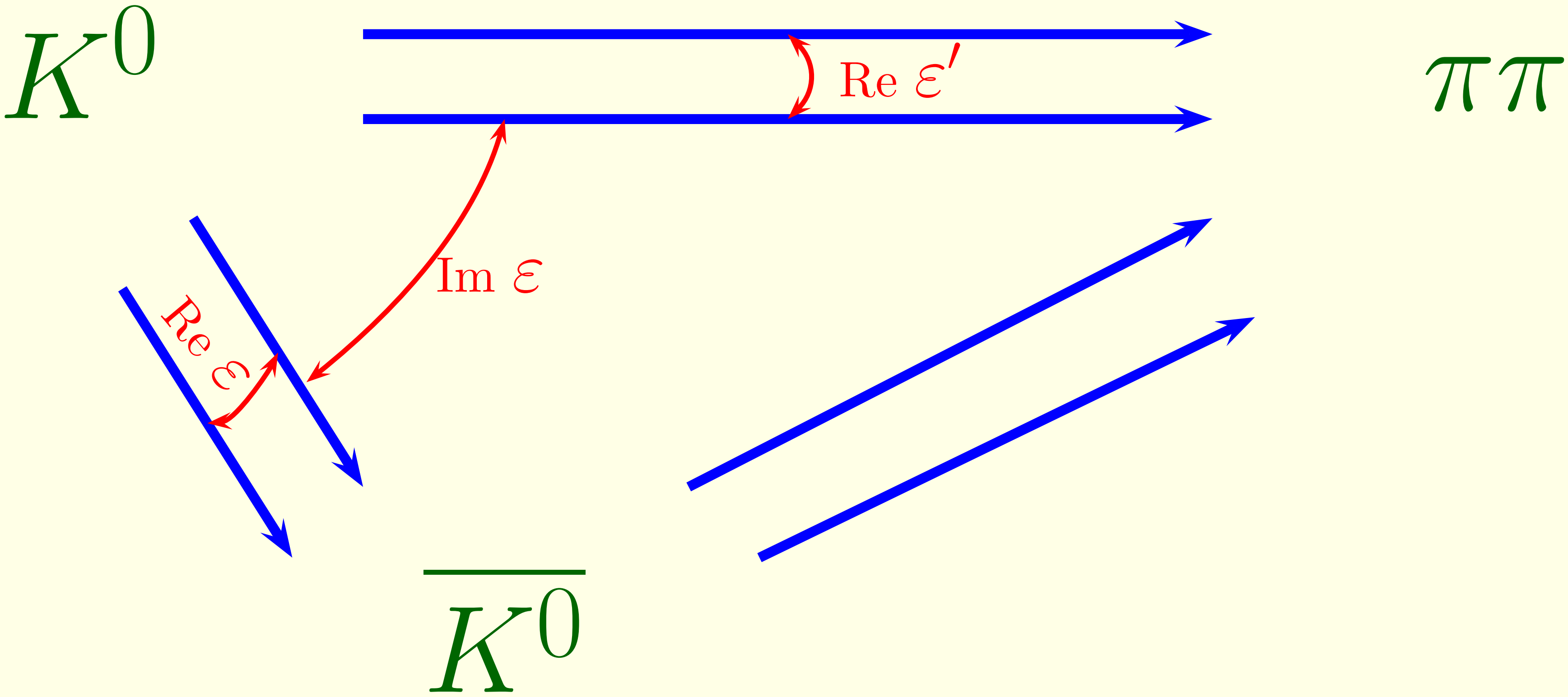
$$\begin{aligned} \mathcal{A}_{f_{\rm CP}}(t) &\equiv \frac{\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{\rm CP}) - \Gamma(B^0_{\rm phys}(t) \to f_{\rm CP})}{\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{\rm CP}) + \Gamma(B^0_{\rm phys}(t) \to f_{\rm CP})} \\ &= -C_{f_{\rm CP}} \cos(\Delta m_B\ t) + S_{f_{\rm CP}} \sin(\Delta m_B\ t) \\ C_{f_{\rm CP}} &= -\mathcal{A}_{f_{\rm CP}} = \frac{1 - |\lambda_{f_{\rm CP}}|^2}{1 + |\lambda_{f_{\rm CP}}|^2}, \quad S_{f_{\rm CP}} = \frac{2\mathcal{I}m\lambda_{f_{\rm CP}}}{1 + |\lambda_{f_{\rm CP}}|^2}. \end{aligned}$$

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

$$\boxed{S_{f_{\rm CP}} = \mathcal{I}m\lambda_{f_{\rm CP}} \sim \sin[\arg(M_{12}) - 2\arg(A)]}$$



$$|\varepsilon| = (2.27 \pm 0.01) \times 10^{-3} \quad \left(\varepsilon = \tfrac{1-\lambda_0}{1+\lambda_0}\right)$$

Christenson, Cronin, Fitch, Turlay (64)

$$\mathcal{R}e\ \varepsilon'/\varepsilon = (1.66 \pm 0.16) \times 10^{-3} \quad \left(\varepsilon' = \tfrac{1}{6}(\lambda_{00} - \lambda_{+-})\right)$$

NA31 (88), KTeV (01), NA48 (02): $(1.47 \pm 0.22) \times 10^{-3}$

Lessons from ε'/ε

- Direct CP violation has been observed.
- The superweak scenario is excluded.

  Wolfenstein (64)
- The result is consistent with the SM predictions.
- Large hadronic uncertainties $\Longrightarrow$ no useful CKM constraint.
- New physics (*e.g.* Supersymmetry) may contribute significantly.

  e.g. Masiero and Murayama (99)

B physics

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

$$\begin{tikzcd}
B^0 \arrow[rr, shift left] \arrow[rr, shift right] \arrow[dr, shift left] \arrow[dr, shift right] & & \psi K_S \\
& \overline{B^0} \arrow[ur, shift left] \arrow[ur, shift right] &
\end{tikzcd}$$

$$\mathcal{I}m\lambda_{\psi K_S} = 0.731 \pm 0.055$$
$$|\lambda_{\psi K}| = \left| \frac{q}{p} \frac{\bar{A}_{\psi K}}{A_{\psi K}} \right| = 0.949 \pm 0.039$$

Belle+Babar (ICHEP02)

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Belle+Babar (ICHEP02)

$$\mathcal{A}_{\rm SL} = 0.002 \pm 0.014 \implies |q/p| = 0.999 \pm 0.007$$
$$\mathcal{A}_{\psi K^\mp} = 0.008 \pm 0.025 \implies |\bar{A}_{\psi K}/A_{\psi K}| = 1.008 \pm 0.025$$
$$\implies |\lambda_{\psi K}| = 1.007 \pm 0.026$$

$$\boxed{\mathcal{I}m\lambda_{\psi K} = 0.734\pm0.054}$$

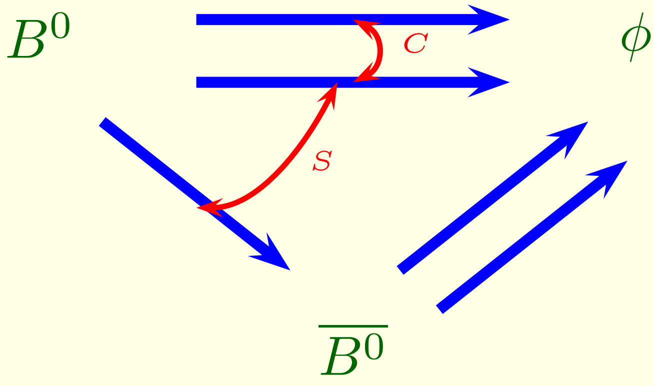
BABAR, BELLE, CDF, ALEPH, OPAL

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.
- Approximate CP (in the sense that all CPV phases are small) is excluded.
- A significant constraint on the CKM parameters $(\bar\rho, \bar\eta)$:

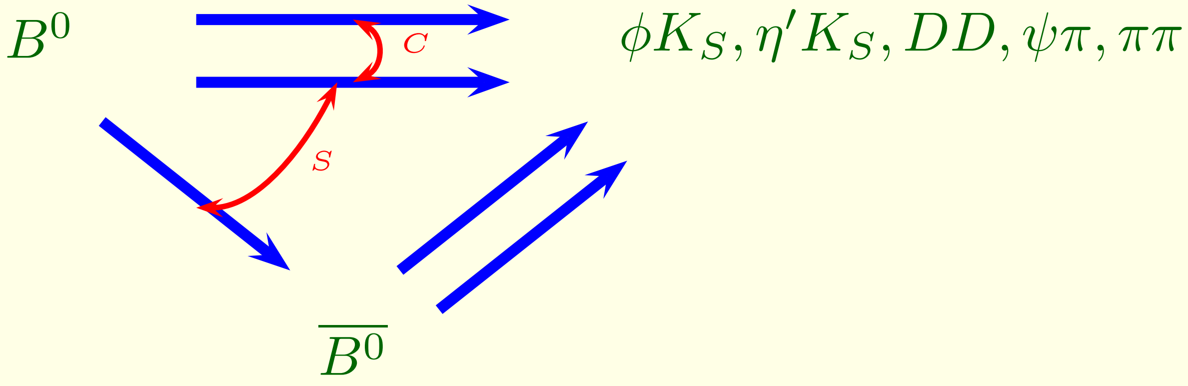
$$\boxed{\mathcal{I}m\lambda_{\psi K_S} = \sin 2\beta = \tfrac{2\bar\eta(1-\bar\rho)}{\bar\eta^2+(1-\bar\rho)^2} = 0.734 \pm 0.054}$$

- New, CPV physics that contributes $> 20\%$ to $B^0 - \overline{B^0}$ mixing is disfavored.



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

				What if $S \neq S_{\psi K_S}$?
ψK_S	$\bar{b} \to \bar{c}c\bar{s}$	T	$\sin 2\beta$	
ϕK_S	$\bar{b} \to \bar{s}s\bar{s}$	P	$\sin 2\beta$	NP
$\eta' K_S$	$\bar{b} \to \bar{s}s\bar{s}$	P	$\sin 2\beta$	NP(?)
$D^* D^*$	$\bar{b} \to \bar{c}c\bar{d}$	$T+P$	$\sin 2\beta_{\text{eff}}$	penguins(?)
$\psi\pi$	$\bar{b} \to \bar{c}c\bar{d}$	$T+P$	$\sin 2\beta_{\text{eff}}$	penguins
$\pi\pi$	$\bar{b} \to \bar{u}u\bar{d}$	$T+P$	$\sin 2\alpha_{\text{eff}}$	direct CPV



$S = \frac{2\mathcal{I}m\lambda}{1+\lvert\lambda\rvert^2}$	$C = \frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}$	$S \neq 0$	$C \neq 0$	$\pm S \neq S_{\psi K}{}^{\dagger}$
$S_{\phi K_S} = -0.39 \pm 0.41$	$C_{\phi K_S} = 0.56 \pm 0.43$	–	–	2.7σ
$S_{\eta' K_S} = +0.76 \pm 0.36$	$C_{\eta' K_S} = -0.26 \pm 0.22$	2.1σ	–	–
$\mathcal{I}m\lambda_{DD} = 0.31 \pm 0.46$	$\lvert\lambda_{DD}\rvert = 0.98 \pm 0.27$	–	–	2.7σ
$S_{\psi\pi} = -0.46 \pm 0.49$	$C_{\psi\pi} = 0.31 \pm 0.29$	–	–	–
$S_{\pi\pi} = -0.48 \pm 0.60$	$C_{\pi\pi} = -0.54 \pm 0.31$	–	–	–

† $+S_{\phi K_S, \eta' K_S}, \quad -S_{DD, \psi\pi, \pi\pi}.$

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

- CPV has not yet been observed in B decays other than $B \to \psi K$.

  (A 2.1σ effect in $\eta' K_S$.)

- Direct CPV has not yet been observed in B decays.

  (2.7σ effects in $S_{\phi K} \leftrightarrow S_{\psi K}$ and in $S_{DD} \leftrightarrow S_{\psi K}$.)

- No evidence of new physics.

  (A 2.7σ effect in $S_{\phi K} \leftrightarrow S_{\psi K}$.)

  Grossman, Isidori, Worah (98)

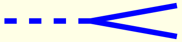
- Define $\mathcal{I}m\lambda_{\pi\pi} \equiv |\lambda_{\pi\pi}| \sin 2\alpha_{\rm eff}$. Then the information on $\mathcal{B}(B \to \pi\pi)$ implies $\sin^2(\alpha_{\rm eff} - \alpha) \leq \mathcal{B}^{00}/\mathcal{B}^{+0} \leq 0.61$

  Grossman and Quinn (98); Charles (99); Gronau, London, Sinha, Sinha (01)

- Small strong phases give $|C_{\pi\pi}| \ll 1$:
  $\Longrightarrow C_{\pi\pi}$ will test QCD factorization.

  Beneke, Buchalla, Neubert, Sachrajda (01); Keum, Li and Sanda (01)

Supersymmetry for Phenomenologists

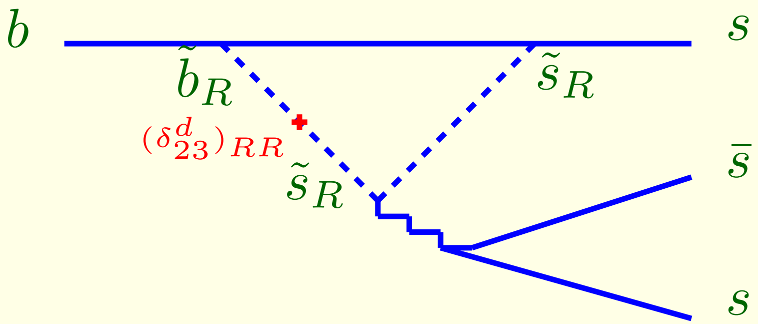
		FV	CPV
	Y	$+$	$+$
	μ	$-$	$+$
	A	$+$	$+$
	$m_{\tilde{g}}$	$-$	$+$
	$m^2_{\tilde{f}}$	$+$	$+$
	B	$-$	$+$

80 real + 44 imaginary parameters

CP Violation in Supersymmetry

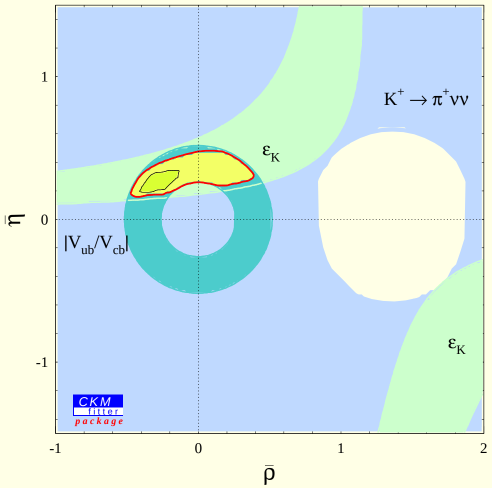
- K physics: $\frac{\mathcal{I}m M_{12}^{\rm SUSY}}{\mathcal{I}m M_{12}^{\rm exp}} \sim 10^8 \left(\frac{100\ GeV}{\tilde m}\right)^2 \left(\frac{\Delta\tilde m_{12}^2}{\tilde m^2}\right)^4 \mathcal{I}m\left[(K_{12}^d)^2\right]$
  - Heavy squarks: $\tilde m \gg 100\ GeV$;
  - Universality: $\Delta\tilde m_{21}^2 \ll \tilde m^2$;
  - Alignment: $|K_{12}^d| \ll 1$;
  - (Approximate CP: $\sin\phi \ll 1$)
- B physics: $S_{\psi K_S}^{\rm exp} \simeq S_{\psi K_S}^{\rm SM}$
  - consistent with exact universality,
  - constrains U(2) and U(1) models, disfavors heavy squarks.
- D physics: $x, y \lesssim 0.05$
  - probes alignment.
- EDMs: $\frac{d_N^{\rm SUSY}}{6.3\times 10^{-26}\ e\ {\rm cm}} \sim 300 \left(\frac{100\ GeV}{\tilde m}\right)^2 \sin\phi_{A,B}$
  - can distinguish MFV ($\lesssim 10^{-31}$) from SUSY CPV ($\gtrsim 10^{-28}$).

SUSY contributions to $B \to \phi K_S$



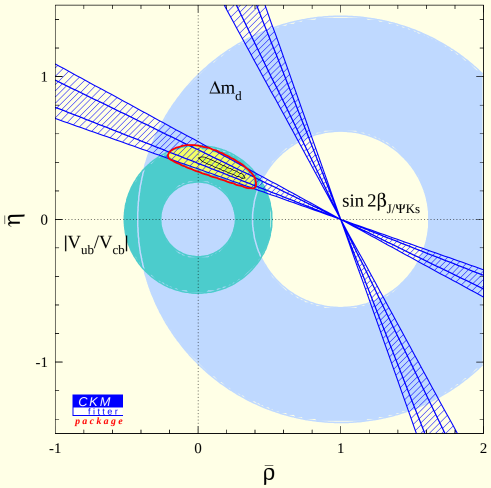
- Could there be large effects in $B \to \phi K_S$ and not in $B \to \psi K_S$?
  Yes: $\delta^d_{23} \leftrightarrow \delta^d_{13}$
- Could there be large effects in $B \to \phi K_S$ and not in $B \to X_s\gamma$?
  Yes: $\delta^d_{RR} \leftrightarrow \delta^d_{LR}$
- Are there well-motivated models with $(\delta^d_{23})_{RR} = \mathcal{O}(1)$?
  - U(1) flavor symmetry: $(\delta^d_{23})_{RR} \sim (m_s/m_b)/|V_{cb}|$
  - SO(10) GUTs: $(\delta^d_{23})_{RR} \sim \theta^\ell_{23}$

Unitarity Triangles, One Last Time...



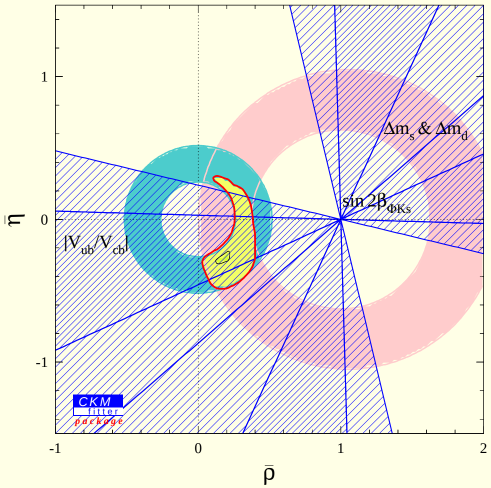
$s \longrightarrow d$

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



$b \longrightarrow d$

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



$b \longrightarrow s$

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

Conclusions

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

- We are leaving the era of hoping for NP alternatives to CKM. (Superweak models and approximate CP - excluded.)

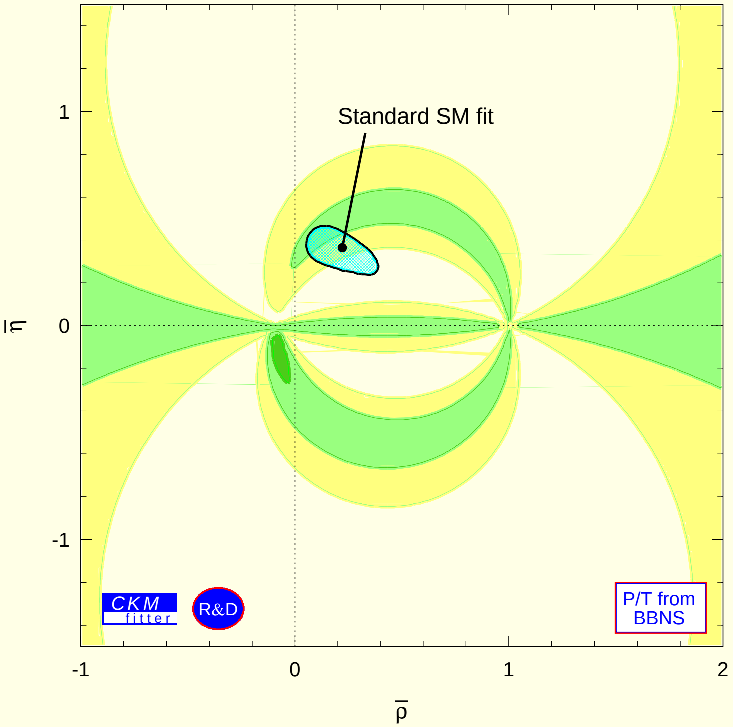
- We are entering the era of seeking for NP corrections to CKM.

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

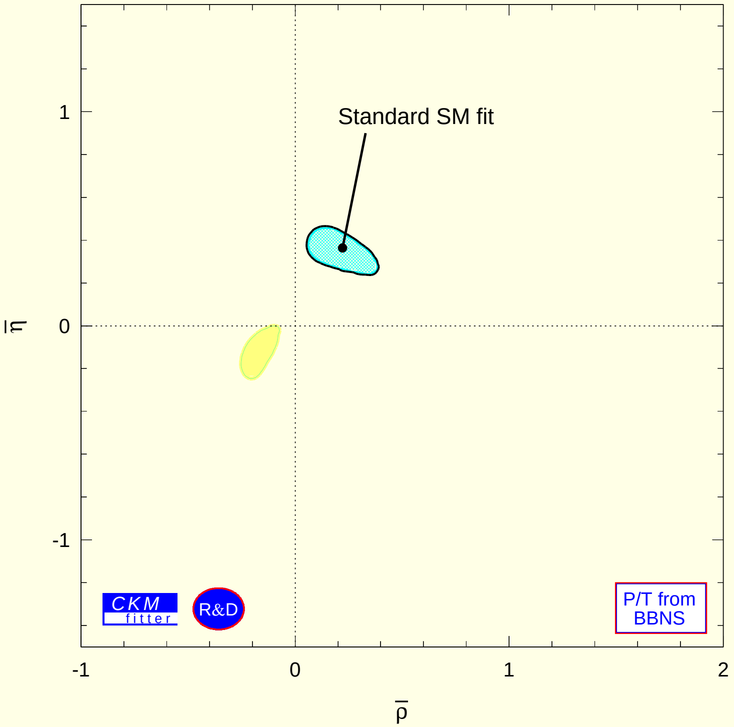
Additional topics

1. γ and α from charmless B decays
2. D physics
3. $K \to \pi\nu\bar{\nu}$
4. Issues in the CKM determination
5. QCD-Improved Factorization
6. Leptogenesis
7. Minimal Flavor Violation (MFV)
8. More on Supersymmetry

α from $C_{\pi\pi}$ and $S_{\pi\pi}$



BABAR data



BELLE data

Experimental input: $C_{\pi\pi}$, $S_{\pi\pi}$

Theoretical input: $|P/T|$ from BBNS

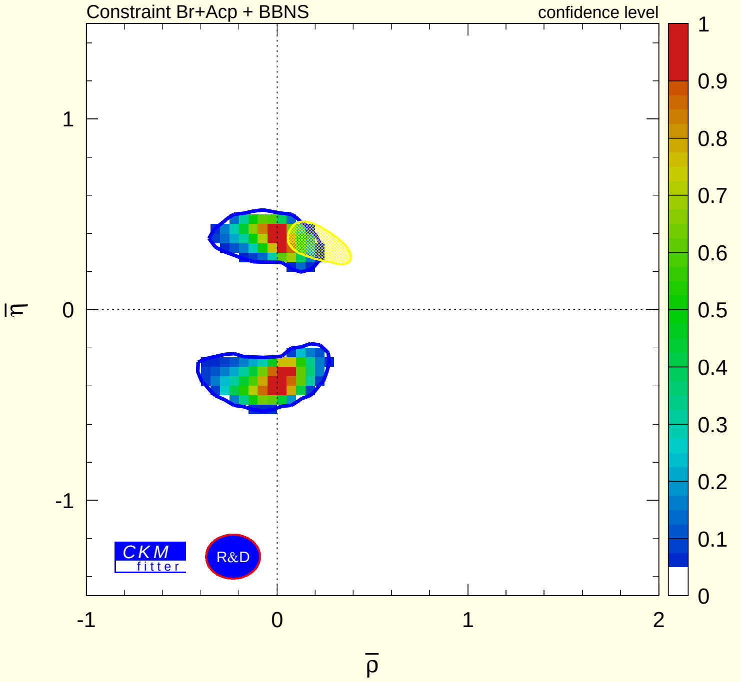
α from isospin analysis of $B \to \pi\pi$

BABAR data BELLE data

Experimental input: $\mathcal{B}^{+-},\ \mathcal{B}^{\pm 0},\ \mathcal{B}^{00},\ \mathcal{A}_{\pi^\mp\pi^0},\ C_{\pi\pi},\ S_{\pi\pi}$

Theoretical input: Isospin (‘Gronau-London’) relations

UT from charmless B decays



Experimental input: $\mathcal{B}(B \to \pi\pi/K\pi)$, $\mathcal{A}_{\mathrm{CP}}$

Theoretical input: BBNS

Model-Independent Bounds

- Fleischer-Mannel (98)

$$R \equiv \frac{\mathcal{B}(B^0\to\pi^-K^+)+\mathrm{B}(\overline{B^0}\to\pi^+K^-)}{\mathcal{B}(B^+\to\pi^+K^0)+\mathrm{B}(B^-\to\pi^-\overline{K^0})} = 1.04 \pm 0.12$$

- Neubert-Rosner (98)

$$R_c \equiv 2\frac{\mathcal{B}(B^+\to\pi^0K^+)+\mathrm{B}(B^-\to\pi^0K^-)}{\mathcal{B}(B^+\to\pi^+K^0)+\mathrm{B}(B^-\to\pi^-\overline{K^0})} = 1.28 \pm 0.19$$

- Buras-Fleischer (99)

$$R_n \equiv \frac{1}{2}\frac{\mathcal{B}(B^0\to\pi^-K^+)+\mathrm{B}(\overline{B^0}\to\pi^+K^-)}{\mathcal{B}(B^0\to\pi^0K^0)+\mathrm{B}(\overline{B^0}\to\pi^0\overline{K^0})} = 1.04 \pm 0.28$$

- With $R_{(c,n)} < 1$, model independent bounds on γ.
- With $R_{(c,n)} > 1$, model dependent bounds on γ.
- With $R_{(c,n)} = 1$, no bounds on γ.

$$\begin{tikzcd}
D^0 \arrow[rr] \arrow[dr, shift left] \arrow[dr, shift right] & & K^+K^- \\
& \overline{D^0} \arrow[ur] &
\end{tikzcd}$$

- Define ($y_{\rm CP} \to y$ in the CP limit)

$$y_{\rm CP} \equiv \frac{\hat{\Gamma}(D\to K^+K^-)}{\hat{\Gamma}(D^0\to\pi^+K^-)} - 1$$

- Assume no direct CP violation:

$$y_{\rm CP} = y\cos\phi - x(|q/p|-1)\sin\phi \qquad (\phi - \pi \equiv \arg\lambda)$$

Bergmann *et al.* (00)

- Experiments (FOCUS, E791, CLEO, BELLE, BABAR):

$$\boxed{y_{\rm CP} = (1.0 \pm 0.7)\times 10^{-2}}$$

$$\begin{tikzcd}
D^0 \arrow[rr] \arrow[dr, shift left] \arrow[dr, shift right] & & K^+\pi^- \\
& \overline{D^0} \arrow[ur] &
\end{tikzcd}$$

- $K^+\pi^- \neq$ CP e.s. $\Longrightarrow$ analysis complicated by strong phases:

$$x' \equiv x\cos\delta + y\sin\delta, \quad y' \equiv y\cos\delta - x\sin\delta$$

- Assume no direct CP violation:

$$\Gamma(D^0(t) \to K^+\pi^-) \propto R + \sqrt{R}|q/p|(y'c_\phi - x's_\phi)\Gamma t + |q/p|^2(y^2+x^2)(\Gamma t)^2/4$$
$$\Gamma(\overline{D^0}(t) \to K^-\pi^+) \propto R + \sqrt{R}|p/q|(y'c_\phi + x's_\phi)\Gamma t + |p/q|^2(y^2+x^2)(\Gamma t)^2/4$$

- Experiment (CLEO):

$$R = (4.8 \pm 1.3)\times 10^{-3}, \quad y' = -0.025^{+0.014}_{-0.016}, \quad x' = 0.000 \pm 0.015$$
$$|q/p|^2 - 1 = 0.23^{+0.63}_{-0.80}, \quad \sin\phi = 0.0 \pm 0.6$$

Interesting new Dalitz analysis of $D \to K^{*+}\pi^-$ (CLEO):

$$\delta = (9 \pm 10 \pm 3^{+15}_{-5})^o$$

Lessons from $D \to KK, K\pi$

- No signal of mixing yet:

	CPV (NP)	CPC (SM)
y	< 0.046	< 0.022
x	< 0.063	< 0.050

- $y = \mathcal{O}(0.01)$ is possible within the SM (phase space effects).

Falk, Grossman, Ligeti, Petrov (02)

- CP violation is important in two ways:

1. CPV would be the only unambiguous signal of NP.
2. CPV has to be taken into account when constraining NP:

	$\phi \neq 0,\ \delta \neq 0$ (NP)	$\phi = 0,\ \delta = 0$ (PDG)
$\frac{\|M_{12}\|}{10^{-11}\ MeV}$	< 5.4	< 2.3

Raz (02)

Back

Littenberg (89)

$$\begin{tikzcd}
K^0 \arrow[rr] \arrow[dr] & & \pi^0\nu\bar{\nu} \\
& \overline{K^0} \arrow[ur] &
\end{tikzcd}$$

- CP violation in mixing and in decay are negligible.
- Hadronic uncertainties are negligible.
- A huge experimental challenge.

- The charged (CPC) mode has been measured by E787:

$$\boxed{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}}$$

Lessons from $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

- Consistent with the SM:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = (0.72 \pm 0.21) \times 10^{-10}$$

Buchalla and Buras (99)

- There is still (much!) room for new physics.

D'Ambrosio and Isidori (01)

- Provides a model-independent upper bound on the K_L-decay:

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 1.7 \times 10^{-9}$$

Grossman and Nir (97)

A more precise measurement would be extremely interesting
both as a CKM constraint and as a probe of new physics

CKM Fit

parameter	$> 5\%$ CL	$> 32\%$ CL
$\bar{\rho}$	$(0.075, 0.38)$	$(0.12, 0.35)$
$\bar{\eta}$	$(0.25, 0.45)$	$(0.28, 0.41)$
$\sin 2\alpha$	$(-0.92, 0.44)$	$(-0.82, 0.24)$
γ	$(36^o, 80^o)$	$(40^o, 73^o)$

How to deal with theoretical uncertainties?

- Scanning method

Plaszczynski and Schune (98)
BaBar Physics Book (98)
Dubois-Felsmann, Hitlin, Porter, Eigen (02)

- Frequentist approach

Hocker, Lacker, Laplace, Le Diberder (01)

- Naive scanning

Buras (01)
Bergmann and Perez (01)

- Gaussian approach

Ali and London (01)
Mele (99)
Atwood and Soni (01)

- Bayesian approach

Ciuchini *et al* (01)
Buras, Parodi, Stocchi (02)

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Buras, Parodi, Stocchi (02)

> "If it is not robust, it is not believable"
>
> Bahcall, Gonzalez-Garcia, Pena-Garay (01)

Factorization in exclusive B-decays

- Consider $B \to M_1 M_2$ where M_2 is a light meson, and M_1 is a light or heavy meason that inherits the spectator quark from B.
- Factorization $\equiv$ There is no long-distance interaction between the constituents of the meson M_2 and the (BM_1) system at leading order in $1/m_b$.
- Factorization for $B \to D^{(*)}\pi$ proved to two-loops by Beneke, Buchalla, Neubert and Sachrajda [BBNS] (01) and to all orders by Bauer, Pirjol and Stewart (02).

$$\langle D\pi|O_i|\bar{B}\rangle = F^{B\to D}\int dx T(x)\phi_\pi(x) f_\pi$$

- For reviews, see e.g. Ligeti (hep-ph/0112089), Beneke (hep-ph/0202056).

Factorization in exclusive $B \to D\pi$

- Factorization:

BBNS (00)

  - $\mathcal{B}(B \to D^0\pi^-)/\mathcal{B}(B \to D^+\pi^-) = 1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_c)$
  - $\delta_{\Delta I=\frac{3}{2}} - \delta_{\Delta I=\frac{1}{2}} = \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_c)$

- Experiment (CLEO, BELLE):
  - $\mathcal{B}(B \to D^0\pi^-)/\mathcal{B}(B \to D^+\pi^-) = 1.85 \pm 0.25$
  - $\sin\delta = 0.5 \pm 0.1$

Charmless B decays

- BBNS: Sudakov suppression ineffective at the B mass scale in the endpoint regions of quark distribution functions.
- KLS ('pQCD'): Sudakov suppression renders the $B \to M_1$ form factor and many power suppressed effects calculable.

  Keum, Li and Sanda (01)
- Different power counting and different phenomenological predictions (e.g. small[BBNS]/large[KLS] strong phases).
- In principle, soft collinear effective theory [SCET] should help to settle these issues. Bauer, Fleming, Pirjol, Stewart (01)
- Experimental data are crucial.

$B \to \pi\pi, K\pi$

- BBNS and KLS predictions vs Experiment (CLEO, BELLE, BABAR):

	BBNS	KLS	World Average
$\frac{\mathcal{B}(\pi^+\pi^-)}{\mathcal{B}(\pi^\mp K^\pm)}$	$0.3 - 1.6$	$0.30 - 0.69$	0.28 ± 0.04
$\frac{\mathcal{B}(\pi^\mp K^\pm)}{2\mathcal{B}(\pi^0 K^0)}$	$0.9 - 1.4$	$0.78 - 1.05$	1.0 ± 0.3
$\frac{2\mathcal{B}(\pi^0 K^\pm)}{\mathcal{B}(\pi^\pm K^0)}$	$0.9 - 1.3$	$0.77 - 1.60$	1.3 ± 0.2
$\frac{\tau_+}{\tau_0}\frac{\mathcal{B}(\pi^\mp K^\pm)}{\mathcal{B}(\pi^\pm K^0)}$	$0.6 - 1.0$	$0.70 - 1.45$	1.1 ± 0.1
$\frac{\tau_+}{\tau_0}\frac{\mathrm{B}(\pi^+\pi^-)}{2\mathrm{B}(\pi^\pm\pi^0)}$	$0.6 - 1.1$		0.56 ± 0.14

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Neutrinos: the data

- AN

$$|\Delta m^2_{32}| = (1.4 - 6.0) \times 10^{-3}\ eV^2$$
$$\tan^2\theta_{23} = 0.4 - 3.0$$

- SN

$$\Delta m^2_{21} = (0.24 - 2.4) \times 10^{-4}\ eV^2$$
$$\tan^2\theta_{12} = 0.27 - 0.77$$

- CHOOZ

$$\sin^2\theta_{13} < 0.06$$

Review: Gonzalez-Garcia and Nir (02)

Implications of Neutrino Masses

- ν's have masses and mix $\Longrightarrow$

  $\boxed{\text{Very likely, CP is violated in the lepton sector}}$

- $m_\nu \ll m_\ell$ naturally explained if ν's are Majorana particles $\Longrightarrow$

  $\boxed{\text{Very likely, lepton number is violated}}$

- $m_\nu \sim 0.05\ eV$ $\Longrightarrow$

  $\boxed{\text{Very likely, there are singlet fermions at } 10^{11} - 10^{15}\ GeV}$

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  $\boxed{\text{Very likely, there are singlet fermions at } 10^{11} - 10^{15}\ GeV}$

$$\Downarrow$$

Everything is ready for Leptogenesis

Fukugita and Yanagida (86)

Leptogenesis

1. At $T \sim M_N$, the singlet fermion drops out of thermal equilibrium and becomes over-abundant.
2. The singlet fermion decays with CP- and L-violating channels, $N \to \ell\phi$ and $N \to \bar{\ell}\bar{\phi}$.
3. The SM sphaleron interactions convert the lepton asymmetry into baryon asymmetry.

$$\Downarrow$$

The final baryon asymmetry depends on four neutrino parameters:

Buchmüller *et al.* (02)

$$\begin{aligned} &M_1 && \sim 10^{10}\ GeV \\ &\tilde{m}_1 = \frac{(M_D^\dagger m_D)_{11}}{M_1} && \sim 10^{-3}\ eV \\ &\bar{m} = [\mathrm{tr}(m_\nu^\dagger m_\nu)]^{1/2} && \sim 0.05\ eV \\ &\epsilon_1 \lesssim \frac{3}{16\pi}\frac{M_1(\Delta m^2_{\mathrm{atm}})^{1/2}}{v^2} && \sim 10^{-6} \end{aligned}$$

Testing Leptogenesis (LG)?

$\oplus$ The baryon asymmetry can be easily accounted for by LG.

$\ominus$ Possible problem with inflation ($T_R \lesssim 10^9\ GeV$ to solve the gravitino problem)

$\ominus$ We will not be able to directly probe the physics of LG.

$\ominus$ The CPV phases that drive LG are, in general, independent of the three CPV phases of the light lepton sector.

Branco *et al.*, Davidson and Ibarra, Ellis and Raidal, Berger and Siyeon (02)

$\oplus$ LG will be made a very plausible scenario if

- $0\nu 2\beta$ decay is observed $\Longrightarrow$ $\boxed{\text{Lepton number is violated}}$
- $P(\nu_\mu \to \nu_e) \neq P(\overline{\nu_\mu} \to \overline{\nu_e})$ is observed $\Longrightarrow$ $\boxed{\text{CPV in the } \nu\text{-sector}}$

Leptogenesis 2002: The Literature

- Branco, Gonzalez Felipe, Joaquim, Rebelo [hep-ph/0202030]
- Rodejohann, Balaji [hep-ph/0201052]
- Fujii, Hamaguchi, Yanagida [hep-ph/0202210,0203189]
- Fukuyama, Okada [hep-ph/0202214]
- Davidson, Ibarra [hep-ph/0202239,0206304]
- Senami, Yamamoto [hep-ph/0205041]
- Bernreuther [hep-ph/0205279]
- Buchmuller, Di Bari, Plumacher [hep-ph/0205349]
- Ellis, Raidal [hep-ph/0206174]
- Murayama, Pierce [hep-ph/0206177]
- Xing [hep-ph/0206245]
- Ellis, Raidal, Yanagida [hep-ph/0206300]
- Asaka, Nielsen, Takanishi [hep-ph/0207023]
- Rodejohann [hep-ph/0207053]

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Minimal Flavor Violation (MFV)

- In the limit of vanishing Yukawa couplings, the SM acquires a global symmetry: $G = [U(3)]^5$.

MFV $\equiv$ The only source of G-breaking are the Yukawa couplings

- A well known (and well motivated) example: The supersymmetric standard model (SSM) with

  1. universal sfermion masses-squared,
  2. A-terms proportional to the Yukawa couplings,
  3. vanishing flavor-diagonal phases.

- If MFV is excluded, new sources of flavor and CP violation (beyond CKM) will be necessary.

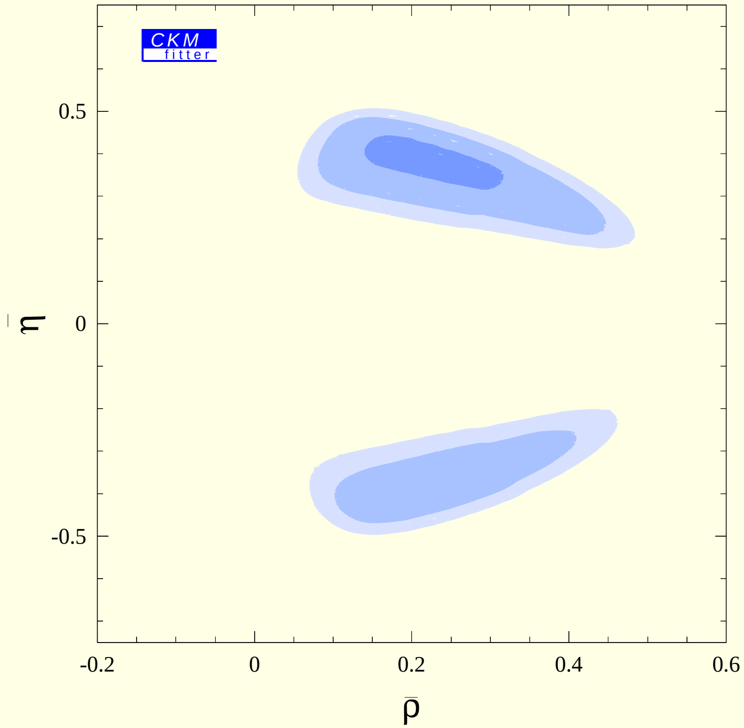
The CKM constraints

- The constraints from $|V_{ub}|$ and $\Delta m_{B_d}/\Delta m_{B_s}$ remain unchanged.
- The constraint from $S_{\psi K_S}$ remains unchanged up to a sign.
- The constraints from ε_K and Δm_B change in a correlated way.

$$\Downarrow$$

The 5 observables depend on 3 parameters: ρ, η, F_{tt}

The MFV UT



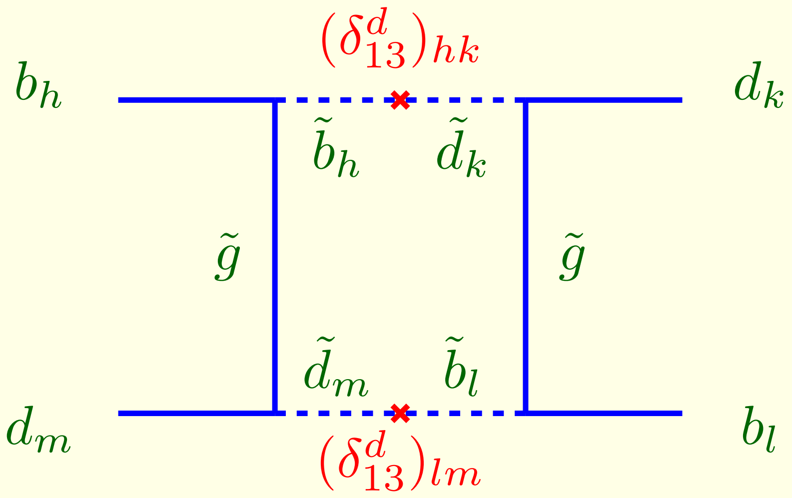
- α and γ could be different from SM.
- $d_j \rightarrow d_i \nu \bar{\nu}$ could be different from SM and are highly correlated.
- For $\tan\beta \gg 1$, interesting effects in $B \rightarrow \ell^+\ell^-$ and $B \rightarrow X\gamma$.
- $\eta < 0$ solution excluded if $f_B > 200\ MeV$.

Back

MFV: The Literature

- Ali, London [hep-ph/0002167]
- Buras, Gambino, Gorbahn, Jager, Silvestrini [hep-ph/0007085,0007313]
- Buras, Buras [hep-ph/0008273]
- Bergmann, Perez [hep-ph/0103299]
- Buras, Fleischer [hep-ph/0104238]
- Buras, Chankowski, Rosiek, Slawianowska [hep-ph/0107048]
- Laplace, Ligeti, Nir, Perez [hep-ph/0202010]
- Buras, Gambino, Jager, Silvestrini [hep-ph/0202030]
- Bobeth, Ewerth, Kruger, Urban [hep-ph/0204225]
- D'Ambrosio, Giudice, Isidori, Strumia [hep-ph/0207036]
- Buras, Gambino, Parodi, Stocchi [hep-ph/0207101]

Constraints from Δm_B and $S_{\psi K_S}$



For $m_{\tilde{q}} = m_{\tilde{g}} = 250\ GeV$:

- $\mathcal{R}e(\delta^d_{13})_{LL=RR} < 0.021$
- $\mathcal{I}m(\delta^d_{13})_{LL=RR} < 0.009$
- $\mathcal{R}e(\delta^d_{13})_{LR=RL} < 0.052$
- $\mathcal{I}m(\delta^d_{13})_{LR=RL} < 0.023$

Becirevic *et al* (01)

- Calculations include NLO QCD corrections.

Ciuchini *et al* (97)
Buras, Misiak, Urban (00)

- Matrix elements computed on the lattice.

Becirevic *et al* (01)

- MIA meaningful also for non-degenerate squarks.

Raz (02)

- Interesting implications for heavy squarks, U(2), alignment.

Masiero, Piai, Romanino, Silvestrini (01)
Goto *et al* (02)
Nir and Raz (02)

Supersymmetry Breaking (SB)

The flavor and CP structure of SUSY models depend on the mechanism of dynamical supersymmetry breaking (DSB)

- $\Lambda_{\rm SB} \ll m_{\rm Pl} \Longrightarrow$ Exact Universality:
  GMSB.
  The only source of FV and CPV are the Yukawa couplings.
  Deviations from SM are very small.

- $\Lambda_{\rm SB} \sim m_{\rm Pl} \Longrightarrow$ Approximate/No Universality:
  AMSB, $\tilde{g}$MSB, Dilaton dominance,
  U(1), U(2), heavy squarks.
  Genuinely new sources of FV and CPV.
  Deviations of order 1-20 percent are likely.

Dine, Kramer, Nir, Shadmi (01)

Masiero and Vives (01)

Neutrinos and Supersymmetry

The interplay between neutrino masses and supersymmetry leads to intriguing relations between various observables

1. SUSY-GUT: neutrino flavor parameters ($\nu_\mu - \nu_\tau$ mixing) are related to singlet-down flavor parameters ($s_R - b_R$ mixing).
   - In (non-universal) SUSY, $s_R - b_R$ mixing has physical consequences via the slepton sector ($\tilde{s}_R - \tilde{b}_R$ mixing).
   - $\theta^\ell_{23} \sim 1 \Longrightarrow \Delta m_{B_s},\ \mathcal{A}_{B_s \to D_s^+ D_s^-},\ \mathcal{A}_{\phi K_S} \leftrightarrow \mathcal{A}_{\psi K_S}$.

   Chang, Masiero, Murayama (02)
2. Minimal SUSY see-saw: the neutrino Yukawa couplings affect m_ν, LG and lepton flavor violation in the slepton sector.
   - The T-odd asymmetry in polarized $\mu \to eee$ is sensitive to the phases relevant to leptogenesis.

   Ellis, Hisano, Lola, Raidal (01)

SUSY 2002: The Literature

- Hiller, Schmaltz [hep-ph/0201251]
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- Khalil [hep-ph/0202204]
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