B mixing and supersymmetry

Ulrich Nierste
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Theory seminar
Fermilab, July 2011
May 17, 2010

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July 9, 2011
New Scientist:

“This result won’t explain all of the matter-antimatter asymmetry,” says Val Gibson at the University of Cambridge, “but it could indicate new physics.” ....

“Supersymmetry can easily explain this measurement”, says Nierste.”
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Higgs doublet \( H = \left( \begin{array}{c} G^+ \\ v + \frac{h^0 + iG^0}{\sqrt{2}} \end{array} \right) \) with \( v = 174 \text{ GeV} \).

Charge-conjugate doublet: \( \tilde{H} = \left( \begin{array}{c} v + \frac{h^0 - iG^0}{\sqrt{2}} \\ -G^- \end{array} \right) \)
SM Yukawa interaction:

Higgs doublet $H = \left( \begin{array}{c} G^+ \\ v + \frac{h^0 + iG^0}{\sqrt{2}} \end{array} \right)$ with $v = 174$ GeV.

Charge-conjugate doublet: $\tilde{H} = \left( \begin{array}{c} v + \frac{h^0 - iG^0}{\sqrt{2}} \\ -G^- \end{array} \right)$

Yukawa lagrangian of quark fields:

$$-L_Y = Y^d_{jk} \overline{Q}^j_L H d^k_R + Y^u_{jk} \overline{Q}^j_L \tilde{H} u^k_R + \text{h.c.}$$

The Yukawa matrices $Y^f$ are arbitrary complex $3 \times 3$ matrices.
SM Yukawa interaction:

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Yukawa lagrangian of quark fields:

\[-L_Y = Y_{jk}^d \overline{Q}_L^j H d_R^k + Y_{jk}^u \overline{Q}_L^j \tilde{H} u_R^k + \text{h.c.}\]

The Yukawa matrices \( Y^f \) are arbitrary complex \( 3 \times 3 \) matrices.

Switch to a basis with diagonal mass matrices \( M^f = Y^f v \).
With three unphysical rotations achieve

\[
\begin{align*}
Y^u &= \hat{Y}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix} \\
Y^d &= V^\dagger \hat{Y}^d
\end{align*}
\]

and

\[
\begin{align*}
\hat{Y}^d &= \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}
\end{align*}
\]

with \( y_i \geq 0 \).

\( V \) is the unitary Cabbibbo-Kobayashi-Maskawa (CKM) matrix.
\[ \Upsilon^u = \hat{\Upsilon}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \]

\[ \Upsilon^d = V^\dagger \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} \]
\[ Y^u = \hat{Y}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \quad Y^d = V^\dagger \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} \]

The last rotation

\[ d^j_L = V_{jk} d^{k'}_L \]

diagonalizes \( Y^d \), but puts \( V \) into the \( W \) boson vertices:

\[ W_\mu \bar{u}^j_L \gamma^\mu d^j_L = W_\mu V_{jk} \bar{u}^j_L \gamma^\mu d^{k'}_L \]
Flavor physics is governed by extremely small numbers:

\[ Y^d \equiv V^\dagger \tilde{Y}^d = \begin{pmatrix} 10^{-5} & -7 \cdot 10^{-5} & (12 + 6i) \cdot 10^{-5} \\ 4 \cdot 10^{-6} & 3 \cdot 10^{-4} & -6 \cdot 10^{-4} \\ (2 + 6i) \cdot 10^{-8} & 10^{-5} & 2 \cdot 10^{-2} \end{pmatrix} \]

evaluated at the energy scale \( m_t \). Off-diagonal element with largest magnitude: \( V_{ts}^* y_b \equiv V_{32}^* y_b = -6 \cdot 10^{-4} \).
Flavor physics is governed by extremely small numbers:

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Flavor violation appears only in charged-current vertices. Flavor-changing neutral current (FCNC) processes are loop suppressed!

\[ \Rightarrow \quad \text{FCNC processes are sensitive to new physics.} \]
Examples of FCNC processes:

- $B_s - \bar{B}_s$ mixing
  - $|\Delta B| = 2$

- Penguin diagram
  - $|\Delta B| = 1$
Examples of **FCNC** processes:

**$B_s - \overline{B}_s$ mixing**

$$|\Delta B| = 2$$

**Penguin diagram**

$$|\Delta B| = 1$$

Sensitivity of $b \to s$ amplitude $A$ to new physics with FCNC parameter $\delta_{\text{FCNC}}$ and scale $\Lambda \gg M_W$:

$$\frac{|A_{NP}|_{\Delta B=2}}{|A_{SM}|_{\Delta B=2}} = \frac{|\delta_{\text{FCNC}}|^2}{|V_{ts}|^2} \frac{M_W^2}{\Lambda^2},$$  

$$\frac{|A_{NP}|_{\Delta B=1}}{|A_{SM}|_{\Delta B=1}} = \frac{|\delta_{\text{FCNC}}|}{|V_{ts}|} \frac{M_W^2}{\Lambda^2}.$$
Examples of **FCNC** processes:

**B_s - \overline{B_s} mixing**

\[ |\Delta B| = 2 \]

**Penguin diagram**

\[ |\Delta B| = 1 \]

Sensitivity of **b → s** amplitude \( A \) to new physics with FCNC parameter \( \delta_{\text{FCNC}} \) and scale \( \Lambda \gg M_W \):

\[
\frac{|A_{\text{NP}}|_{\Delta B=2}}{|A_{\text{SM}}|_{\Delta B=2}} = \frac{|\delta_{\text{FCNC}}|^2 M_W^2}{V_{ts}^2 \Lambda^2},
\]

\[
\frac{|A_{\text{NP}}|_{\Delta B=1}}{|A_{\text{SM}}|_{\Delta B=1}} = \frac{|\delta_{\text{FCNC}}| M_W^2}{V_{ts} \Lambda^2}.
\]

\[ \Rightarrow \] Meson-antimeson mixing is more sensitive to generic NP than FCNC decay amplitudes, if \( |\delta_{\text{FCNC}}| > |V_{ts}| \).
Expand the CKM matrix $V$ in $V_{us} \simeq \lambda = 0.2254$:

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
 \simeq
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3 \left(1 + \frac{\lambda^2}{2}\right)(\bar{\rho} - i\bar{\eta}) \\
-\lambda - iA^2\lambda^5\bar{\eta} & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 - iA\lambda^4\bar{\eta} & 1
\end{pmatrix}
$$

with the Wolfenstein parameters $\lambda$, $A$, $\bar{\rho}$, $\bar{\eta}$

CP violation $\Leftrightarrow \bar{\eta} \neq 0$
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\end{pmatrix}
$$

with the Wolfensteinn parameters $\lambda$, $A$, $\bar{\rho}$, $\bar{\eta}$

CP violation $\Leftrightarrow \bar{\eta} \neq 0$

**Unitarity triangle:**

**Exact definition:**

$$
\bar{\rho} + i\bar{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} = \left| \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \right| e^{i\gamma}
$$

$$
A = (\bar{\rho}, \bar{\eta})
$$

$$
\bar{\rho} + i\bar{\eta} = 1 - \bar{\rho} - i\bar{\eta}
$$

$$
C = (0,0)
$$

$$
B = (1,0)
$$
New-physics analysers:

- **Global fit to UT**: overconstrain $(\rho, \eta)$, probes FCNC processes $K - \bar{K}$, $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing.
New-physics analysers:

- **Global fit to UT:** overconstrain \((\bar{\rho}, \bar{\eta})\), probes FCNC processes \(K \rightarrow \bar{K}, B_d \rightarrow \bar{B}_d\) and \(B_s - \bar{B}_s\) mixing.

- **Global fit to \(B_s - \bar{B}_s\) mixing:** mass difference \(\Delta m_s\), width difference \(\Delta \Gamma_s\), CP asymmetries in \(B_s \rightarrow J/\psi \phi\) and \((\bar{B}_s) \rightarrow X \ell \nu_\ell\).
New-physics analysers:

- **Global fit to UT**: overconstrain \((\bar{\rho}, \bar{\eta})\), probes FCNC processes \(K^-K^+\), \(B_d - \bar{B}_d\) and \(B_s - \bar{B}_s\) mixing.
- **Global fit to \(B_s - \bar{B}_s\) mixing**: mass difference \(\Delta m_s\), width difference \(\Delta \Gamma_s\), CP asymmetries in \(B_s \rightarrow J/\psi \phi\) and \(\bar{B}_s \rightarrow X \ell \nu \ell\).
- **Penguin decays**: \(B \rightarrow X_s \gamma\), \(B \rightarrow X_s \ell^+ \ell^-\), \(B \rightarrow K \pi\), \(B_d \rightarrow \phi K_S\), \(B_s \rightarrow \mu^+ \mu^-\), \(K \rightarrow \pi \nu \bar{\nu}\).
New-physics analysers:

- **Global fit to UT**: overconstrain \((\rho, \eta)\), probes FCNC processes \(K - \bar{K}\), \(B_d - \bar{B}_d\) and \(B_s - \bar{B}_s\) mixing.
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- **Penguin decays**: \(B \to X_s \gamma\), \(B \to X_s \ell^+ \ell^-\), \(B \to K \pi\), \(B_d \to \phi K_S\), \(B_s \to \mu^+ \mu^-\), \(K \to \pi \nu \bar{\nu}\).
- **CKM-suppressed or helicity-suppressed tree-level decays**: \(B^+ \to \tau^+ \nu\), \(B \to \pi \ell \nu\), \(B \to D \tau \nu\), probe charged Higgses and right-handed W-couplings.
Global fit in the SM from CKMfitter:

Statistical method: Rfit, a Frequentist approach.
Global fit in the SM from UTfit:

Statistical method: Bayesian.
CKM matrix $V$

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

fixed by measurements of

$$|V_{us}| = 0.2254 \pm 0.0013,$$

$$|V_{cb}| = (40.9 \pm 0.7) \cdot 10^{-3}$$

and a global fit to $(\bar{\rho}, \bar{\eta})$
CKM matrix $V$

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

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and a global fit to $(\rho, \eta)$

Unitarity triangle:

$$\bar{\rho} + i \bar{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}$$
$$= \left| \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \right| e^{i\gamma}$$

A=$(\bar{\rho}, \bar{\eta})$
B=$(1, 0)$
C=$(0, 0)$
The $|V_{ub}|$ puzzle

Three ways to measure $|V_{ub}|$:

- exclusive decay $B \rightarrow \pi \ell \nu$,
- inclusive decay $B \rightarrow X \ell \nu$ and
- leptonic decay $B^+ \rightarrow \tau^+ \nu_{\tau}$.
The $|V_{ub}|$ puzzle

Three ways to measure $|V_{ub}|$:

- exclusive decay $B \rightarrow \pi \ell \nu$, 
- inclusive decay $B \rightarrow X \ell \nu$ and
- leptonic decay $B^+ \rightarrow \tau^+ \nu_{\tau}$.

Average of several BaBar and Belle measurements:

$$B^{\text{exp}}(B^+ \rightarrow \tau^+ \nu_{\tau}) = (1.68 \pm 0.31) \cdot 10^{-4}$$

Standard Model:

$$B(B^+ \rightarrow \tau^+ \nu_{\tau}) = 1.13 \cdot 10^{-4} \cdot \left(\frac{|V_{ub}|}{4 \cdot 10^{-3}}\right)^2 \left(\frac{f_B}{200 \text{ MeV}}\right)^2$$
The $|V_{ub}|$ puzzle

\[ |V_{ub,\text{excl}}| = (3.51 \pm 0.47) \cdot 10^{-3} \]

\[ |V_{ub,\text{incl}}| = (4.32 \pm 0.50) \cdot 10^{-3} \]

\[ |V_{ub,B\rightarrow\tau\nu}| = (5.10 \pm 0.59) \cdot 10^{-3} \]
The $|V_{ub}|$ puzzle

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Here $f_B = (191 \pm 13)$ MeV is used:

$|V_{ub,B\rightarrow\tau\nu}| = \left[5.10 \pm 0.47|_{\text{exp}} \pm 0.35|_{f_B}\right] \cdot 10^{-3}$

$= \left[5.10 \pm 0.59\right] \cdot 10^{-3}$
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$= [5.10 \pm 0.59] \cdot 10^{-3}$

$\Rightarrow$ no puzzle with individual $|V_{ub}|$ determinations
The $|V_{ub}|$ puzzle

Indirect determination:

find $|V_{ub}| \propto |V_{cb}| R_u$

from $R_u = \frac{\sin \beta}{\sin \alpha}$

With $\alpha = 89^\circ \pm 4.4^\circ$ and $\beta = 21.15^\circ \pm 0.89^\circ$ find

$|V_{ub}|_{\text{ind}} = (3.41 \pm 0.15) \cdot 10^{-3}$

Essential: $\beta$ from $A_{\text{CP}}^{\text{mix}}(B_d \rightarrow J/\psi K_S)$
The $|V_{ub}|$ puzzle

$|V_{ub, \text{excl}}| = (3.51 \pm 0.47) \cdot 10^{-3}$

$|V_{ub, \text{incl}}| = (4.32 \pm 0.50) \cdot 10^{-3}$

$|V_{ub, B \to \tau \nu}| = (5.10 \pm 0.59) \cdot 10^{-3}$

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The $|V_{ub}|$ puzzle

$|V_{ub,\text{excl}}| = (3.51 \pm 0.47) \cdot 10^{-3}$

$|V_{ub,\text{incl}}| = (4.32 \pm 0.50) \cdot 10^{-3}$

$|V_{ub,B\to\tau\nu}| = (5.10 \pm 0.59) \cdot 10^{-3}$

$|V_{ub,\text{ind}}| = (3.41 \pm 0.15) \cdot 10^{-3}$

Alleviate the $2.9 \sigma$ tension between $|V_{ub,\text{ind}}|$ and $|V_{ub,B\to\tau\nu}|$ with new physics in

- $B^+ \to \tau^+ \nu_\tau$
  
  E.g. right-handed $W$ coupling, possible in SUSY through loop effects.

Crivellin 2009
The $|V_{ub}|$ puzzle

$|V_{ub,excl}| = (3.25 \pm 0.30) \cdot 10^{-3}$

$|V_{ub,incl}| = (4.25 \pm 0.25) \cdot 10^{-3}$

$|V_{ub,B\rightarrow\tau\nu}| = (5.04 \pm 0.64) \cdot 10^{-3}$

$|V_{ub,ind}| = (3.41 \pm 0.15) \cdot 10^{-3}$

Alleviate the 2.9σ tension between $|V_{ub,ind}|$ and $|V_{ub,B\rightarrow\tau\nu}|$ with new physics in

- $B^+ \rightarrow \tau^+\nu_\tau$ or
- $A_{CP}^{mix}(B_d \rightarrow J/\psi K_S)$. ← easier!
$B - \overline{B}$ mixing in the Standard Model

$B_q - \overline{B}_q$ mixing with $q = d$ or $q = s$ involves the $2 \times 2$ matrices $M$ and $\Gamma$. 
**B – B** mixing in the Standard Model

**B**\(_q\) – **B**\(_\bar{q}\) mixing with \(q = d\) or \(q = s\) involves the 2 × 2 matrices \(M\) and \(\Gamma\).

The **mass matrix element** \(M^q_{12}\) stems from the **dispersive** (real) part of the box diagram, internal \(t\).

The **decay matrix element** \(\Gamma^q_{12}\) stems from the **absorptive** (imaginary) part of the box diagram, internal \(c, u\).
$\mathbf{B} - \overline{\mathbf{B}}$ mixing in the Standard Model

$\mathbf{B}_q - \overline{\mathbf{B}}_q$ mixing with $q = d$ or $q = s$ involves the $2 \times 2$ matrices $M$ and $\Gamma$.

The mass matrix element $M^q_{12}$ stems from the dispersive (real) part of the box diagram, internal $t$.

The decay matrix element $\Gamma^q_{12}$ stems from the absorbive (imaginary) part of the box diagram, internal $c, u$.

3 physical quantities in $\mathbf{B}_q - \overline{\mathbf{B}}_q$ mixing:

$$|M^q_{12}|, \quad |\Gamma^q_{12}|, \quad \phi_q \equiv \arg \left( -\frac{M^q_{12}}{\Gamma^q_{12}} \right)$$
The two eigenstates found by diagonalising $M - i \frac{\Gamma}{2}$ differ in their masses and widths:

mass difference \[ \Delta m_q \approx 2|M_{12}^q|, \]
width difference \[ \Delta \Gamma_q \approx 2|\Gamma_{12}^q| \cos \phi_q \]
The two eigenstates found by diagonalising $M - i \Gamma / 2$ differ in their masses and widths:

\[
\Delta m_q \approx 2|M^q_{12}|, \\
\Delta \Gamma_q \approx 2|\Gamma^q_{12}| \cos \phi_q
\]

CP asymmetry in flavor-specific decays (semileptonic CP asymmetry):

\[
a_{fs}^q = \frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin \phi_q
\]
May 14, 2010: $\textbf{DØ}$ presents

$$a_{fs} = (-9.57 \pm 2.51 \pm 1.46) \cdot 10^{-3}$$

for a mixture of $B_d$ and $B_s$ mesons with

$$a_{fs} = (0.506 \pm 0.043)a_{fs}^d + (0.494 \pm 0.043)a_{fs}^s$$

The result is $3.2\sigma$ away from $a_{fs}^{\text{SM}} = (-0.20 \pm 0.03) \cdot 10^{-3}$.

A. Lenz, UN, 2006 and 2011

Averaging with an older CDF measurement yields

$$a_{fs} = (-8.5 \pm 2.8) \cdot 10^{-3},$$

which is $2.9\sigma$ away from $a_{fs}^{\text{SM}}$. 
DØ result presented 30 Jun 2011:

\[ a_{fs} = (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \]

This differs from the SM value by 3.9\(\sigma\)!
Generic new physics

Phases $\phi_q = \arg(-M_{12}^q / \Gamma_{12}^q)$ in the Standard Model:

$\phi_d^{\text{SM}} = -4.3^\circ \pm 1.4^\circ$, \hspace{1cm} $\phi_s^{\text{SM}} = 0.2^\circ$.

Define the complex parameters $\Delta_d$ and $\Delta_s$ through

$$M_{12}^q \equiv M_{12}^{\text{SM},q} \cdot \Delta_q, \hspace{1cm} \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}.$$ 

In the Standard Model $\Delta_q = 1$. Use $\phi_s = \phi_s^{\text{SM}} + \phi_s^\Delta \simeq \phi_s^\Delta$. 
Phases $\phi_q = \arg(-M_{12}^q/\Gamma_{12}^q)$ in the Standard Model:

$\phi_d^{SM} = -4.3^\circ \pm 1.4^\circ$, $\phi_s^{SM} = 0.2^\circ$.

Define the complex parameters $\Delta_d$ and $\Delta_s$ through

$$M_{12}^q \equiv M_{12}^{SM,q} \cdot \Delta_q, \quad \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}.$$ 

In the Standard Model $\Delta_q = 1$. Use $\phi_s = \phi_s^{SM} + \phi_s^\Delta \simeq \phi_s^\Delta$.

The measurements

$$\Delta m_s = (17.77 \pm 0.10 \pm 0.07) \text{ ps}^{-1} \quad \text{CDF}$$
$$\Delta m_s = (17.63 \pm 0.11 \pm 0.04) \text{ ps}^{-1} \quad \text{LHCb (prelim)}$$

imply

$$|\Delta_s| = 1.03 \pm 0.14_{(th)} \pm 0.01_{(exp)}$$
Confront the DØ/CDF average

\[ a_{fs} = (0.506 \pm 0.043) a_{fs}^d + (0.494 \pm 0.043) a_{fs}^s \]

\[ = (-8.5 \pm 2.8) \cdot 10^{-3} \]

with (A. Lenz, UN, 2011)

\[ a_{fs}^d = (5.4 \pm 1.0) \cdot 10^{-3} \cdot \sin \phi_d / |\Delta_d|, \]

\[ a_{fs}^s = (5.1 \pm 1.0) \cdot 10^{-3} \cdot \sin \phi_s / |\Delta_s|. \]
Confront the DØ/CDF average

\[ a_{fs} = (0.506 \pm 0.043)a_{fs}^d + (0.494 \pm 0.043)a_{fs}^s = (-8.5 \pm 2.8) \cdot 10^{-3} \]

with (A. Lenz, UN, 2011)

\[ a_{fs}^d = (5.4 \pm 1.0) \cdot 10^{-3} \cdot \frac{\sin \phi_d}{|\Delta_d|}, \quad a_{fs}^s = (5.1 \pm 1.0) \cdot 10^{-3} \cdot \frac{\sin \phi_s}{|\Delta_s|}. \]

⇒ Need both \( \phi_s < 0 \) and \( \phi_d < 0 \).
Confront the DØ/CDF average

\[ a_{fs} = (0.506 \pm 0.043)a_{fs}^d + (0.494 \pm 0.043)a_{fs}^s \]
\[ = (-8.5 \pm 2.8) \cdot 10^{-3} \]

with (A. Lenz, UN, 2011)

\[ a_{fs}^d = (5.4 \pm 1.0) \cdot 10^{-3} \cdot \frac{\sin \phi_d}{|\Delta_d|}, \quad a_{fs}^s = (5.1 \pm 1.0) \cdot 10^{-3} \cdot \frac{\sin \phi_s}{|\Delta_s|}. \]

⇒ Need both \( \phi_s < 0 \) and \( \phi_d < 0 \).

\[ A_{CP}^{mix}(B_d \rightarrow J/\psi K_S) \propto \sin(2\beta + \phi_d^A): \]

With \( \phi_d^A < 0 \) find \( \beta > \beta^{SM} = 21^\circ \) ⇒ \( |V_{ub}| \) puzzle solvable.
Global analysis of $B_s - \bar{B}_s$ mixing and $B_d - \bar{B}_d$ mixing

Based on work with A. Lenz and the CKMfitter Group
(J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold,
H. Lacker, S. Monteil, V. Niess)
arXiv:1008.1593

Rfit method: No statistical meaning is assigned to systematic
errors and theoretical uncertainties.

We have performed a simultaneous fit to the Wolfenstein
parameters and to the new physics parameters $\Delta_s$ and $\Delta_d$:

$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^{q;SM}}, \quad \Delta_q \equiv |\Delta_q|e^{i\phi_q^\Delta}.$$
Result for $B_d - \overline{B}_d$ mixing:

SM point $\Delta_d = 1$
disfavored by $2.7\sigma$.

Main driver:
$B^+ \rightarrow \tau^+ \nu_\tau$
Result for $B_s - \bar{B}_s$ mixing:

SM point $\Delta_s = 1$ disfavored by $2.7\sigma$.

without 2010 CDF/DØ and 2011 LHCb data on $B_s \rightarrow J/\psi\phi$.
p-values:
Calculate $\chi^2 / N_{dof}$ with and without a hypothesis to find:

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<td>$3.8 , \sigma$</td>
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Fit result at 95%CL:

\[ \phi_s^\Delta = (-52^{+32}_{-25})^\circ \quad \text{(and } \phi_s^\Delta = (-130^{+28}_{-28})^\circ) \]

Compare with the 2010 CDF/DØ result from \( B_s \to J/\psi \phi \):

CDF: \( \phi_s^\Delta = (-27^{+44}_{-49})^\circ \) at 95%CL

DØ: \( \phi_s^\Delta = (-42^{+59}_{-51})^\circ \) at 95%CL

Naive average: \( \phi_s^{\text{avg}} = (-36 \pm 35)^\circ \) at 95%CL

DØ EPS 2011: \( \phi_s^\Delta = (-30^{+22}_{-21})^\circ \) at 68%CL

LHCb Beauty 2011: \(-199^\circ \leq \phi_s^\Delta \leq 13^\circ \) at 95%CL
Is the result driven by the DØ dimuon asymmetry? One can remove $a_{fs}$ as an input and instead predict it from the global fit:

$$a_{fs} = \left(-4.2^{+2.9}_{-2.7}\right) \cdot 10^{-3} \quad \text{at } 2\sigma.$$
Is the result driven by the DØ dimuon asymmetry? One can remove $a_{fs}$ as an input and instead predict it from the global fit:

$$a_{fs} = \left(-4.2^{+2.9}_{-2.7}\right) \cdot 10^{-3} \quad \text{at } 2\sigma.$$ 

This is just $1.5\sigma$ away from the DØ/CDF average

$$a_{fs} = (-8.5 \pm 2.8) \cdot 10^{-3}.$$ 

$1.6\sigma$ discrepancy (Rfit method) with new DØ result

$$a_{fs} = (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3}.$$
A fit to a real parameter $\Delta = \Delta_s = \Delta_d$ is not better than the SM fit and gives $\Delta = 0.90^{+0.31}_{-0.10}$ at $2\sigma$. 
A fit to a real parameter $\Delta = \Delta_s = \Delta_d$ is not better than the SM fit and gives $\Delta = 0.90^{+0.31}_{-0.10}$ at $2\sigma$.

$\Rightarrow$ bad news for CMSSM and mSUGRA
The **MSSM** has many new sources of flavor violation, all in the supersymmetry-breaking sector.

No problem to get big effects in $B_s - \bar{B}_s$ mixing, but rather to suppress the big effects elsewhere.
Squark mass matrix

Diagonalize the Yukawa matrices $Y^u_{jk}$ and $Y^d_{jk}$

$\Rightarrow$ quark mass matrices are diagonal, super-CKM basis
Squark mass matrix

Diagonalize the Yukawa matrices $Y^u_{jk}$ and $Y^d_{jk}$
⇒ quark mass matrices are diagonal, super-CKM basis

E.g. Down-squark mass matrix:

$$M^2_{\tilde{d}} = \begin{pmatrix}
(M_{1L}^{\tilde{d}})^2 & \Delta_{12}^{\tilde{d}LL} & \Delta_{13}^{\tilde{d}LL} & \Delta_{11}^{\tilde{d}LR} & \Delta_{12}^{\tilde{d}LR} & \Delta_{13}^{\tilde{d}LR} \\
\Delta_{12}^{\tilde{d}LL} & (M_{2L}^{\tilde{d}})^2 & \Delta_{23}^{\tilde{d}LL} & \Delta_{12}^{\tilde{d}RL} & \Delta_{13}^{\tilde{d}RL} & \Delta_{23}^{\tilde{d}RL} \\
\Delta_{13}^{\tilde{d}LL} & \Delta_{23}^{\tilde{d}LL} & (M_{3L}^{\tilde{d}})^2 & \Delta_{13}^{\tilde{d}RR} & \Delta_{12}^{\tilde{d}RR} & \Delta_{23}^{\tilde{d}RR} \\
\Delta_{11}^{\tilde{d}LR} & \Delta_{12}^{\tilde{d}RL} & \Delta_{13}^{\tilde{d}RR} & (M_{1R}^{\tilde{d}})^2 & \Delta_{12}^{\tilde{d}RR} & \Delta_{13}^{\tilde{d}RR} \\
\Delta_{12}^{\tilde{d}LR} & \Delta_{22}^{\tilde{d}RL} & \Delta_{23}^{\tilde{d}RR} & \Delta_{12}^{\tilde{d}RR} & (M_{2R}^{\tilde{d}})^2 & \Delta_{23}^{\tilde{d}RR} \\
\Delta_{13}^{\tilde{d}LR} & \Delta_{23}^{\tilde{d}LR} & \Delta_{33}^{\tilde{d}RR} & \Delta_{13}^{\tilde{d}RR} & \Delta_{23}^{\tilde{d}RR} & (M_{3R}^{\tilde{d}})^2
\end{pmatrix}$$
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E.g. Down-squark mass matrix:

$$M^2_{\tilde{d}} = \begin{pmatrix}
(M^\tilde{d}_{1L})^2 & \Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{13} & \Delta^\tilde{d}_{11} & \Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{13} \\
\Delta^\tilde{d}_{12} & (M^\tilde{d}_{2L})^2 & \Delta^\tilde{d}_{23} & \Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{13} & \Delta^\tilde{d}_{23} \\
\Delta^\tilde{d}_{13} & \Delta^\tilde{d}_{23} & (M^\tilde{d}_{3L})^2 & \Delta^\tilde{d}_{13} & \Delta^\tilde{d}_{23} & \Delta^\tilde{d}_{33} \\
\Delta^\tilde{d}_{11} & \Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{13} & (M^\tilde{d}_{1R})^2 & \Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{13} \\
\Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{11} & \Delta^\tilde{d}_{12} & \Delta^\tilde{d}_{13} & (M^\tilde{d}_{2R})^2 & \Delta^\tilde{d}_{23} \\
\Delta^\tilde{d}_{13} & \Delta^\tilde{d}_{23} & \Delta^\tilde{d}_{33} & \Delta^\tilde{d}_{13} & \Delta^\tilde{d}_{23} & (M^\tilde{d}_{3R})^2
\end{pmatrix}$$

Not diagonal! ⇒ new FCNC transitions.
\[ \delta_{ij}^{q_{LL}} = \frac{\Delta_{ij}^{\tilde{q}_{LL}}}{\frac{1}{6} \sum_s M_{\tilde{q}_{ss}}^2}, \quad q = u, d \]
Flavor and SUSY GUT

Linking quarks to neutrinos: Flavor mixing:
quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix
leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider $SU(5)$ multiplets:

\[
\begin{align*}
\bar{5}_1 &= \begin{pmatrix} 
d^c_R \\
d^c_R \\
d^c_R \\
e_L \\
-\nu_e 
\end{pmatrix}, & \quad \bar{5}_2 &= \begin{pmatrix} 
s^c_R \\
s^c_R \\
\mu_L \\
-\nu_\mu 
\end{pmatrix}, & \quad \bar{5}_3 &= \begin{pmatrix} 
b^c_R \\
b^c_R \\
\tau_L \\
-\nu_\tau 
\end{pmatrix}.
\end{align*}
\]

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\bar{5}_2$ and $\bar{5}_3$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi; Chang, Masiero, Murayama).

⇒ new $b_R - s_R$ transitions from gluino–squark loops possible.
Key ingredients: Some weak basis with

$$Y_d = V_{\text{CKM}}^* \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_{\text{PMNS}}$$

and right-handed down squark mass matrix:

$$m_{\tilde{d}}^2 (M_Z) = \text{diag} \left( m_{\tilde{d}}^2, m_{\tilde{d}}^2, m_{\tilde{d}}^2 - \Delta_{\tilde{d}} \right).$$

with a calculable real parameter $\Delta_{\tilde{d}}$, typically generated by top-Yukawa RG effects.
Rotating $Y_d$ to diagonal form puts the large atmospheric neutrino mixing angle into $m_{d}^2$:

$$U_{PMNS}^\dagger m_{d}^2 U_{PMNS} = \begin{pmatrix} m_{d}^2 & 0 & 0 \\ 0 & m_{d}^2 - \frac{1}{2} \Delta_{\tilde{d}} & -\frac{1}{2} \Delta_{\tilde{d}} e^{i\xi} \\ 0 & -\frac{1}{2} \Delta_{\tilde{d}} e^{-i\xi} & m_{\tilde{d}}^2 - \frac{1}{2} \Delta_{\tilde{d}} \end{pmatrix}$$

The CP phase $\xi$ affects $B_s - \bar{B_s}$ mixing!
The Chang–Masiero–Murayama (CMM) model is based on the symmetry breaking chain
\[ \text{SO}(10) \rightarrow \text{SU}(5) \rightarrow \text{SU}(3) \times \text{SU}(2)_L \times \text{U}(1)_Y. \]
The Chang–Masiero–Murayama (CMM) model is based on the symmetry breaking chain
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\[ \text{SO}(10) \text{ superpotential:} \]

\[ W_Y = \frac{1}{2} 16_i Y_{ij}^{16} 16_j 10_H + \frac{1}{2} 16_i Y_{ij}^{16} 16_j \frac{45_H 10'_H}{M_{\text{Pl}}} \]

\[ + \frac{1}{2} 16_i Y_{ij}^{16} 16_j \frac{16_H 16_H}{M_{\text{Pl}}} \]

with the Planck mass \( M_{\text{Pl}} \) and
- \( 16_i \): one matter superfield per generation, \( i = 1, 2, 3 \),
- \( 10_H \): Higgs superfield containing MSSM Higgs superfield \( H_u \),
- \( 10'_H \): Higgs superfield containing MSSM superfield \( H_u \),
- \( 45_H \): Higgs superfield in adjoint representation,
- \( 16_H \): Higgs superfield in spinor representation.
“Most minimal flavor violation”
The Yukawa matrices $Y_u$ and $Y_N$ are always symmetric. In the CMM model they are assumed to be simultaneously diagonalizable at the scale $M_{Pl}$, where the soft SUSY-breaking terms are universal.
Realistic GUTs involve further dimension-5 Yukawa terms to fix the Yukawa unification in the first two generations. One can use these terms to shuffle a part of the effect from $b_R \rightarrow s_R$ into $b_R \rightarrow d_R$ transitions. This “leakage” is strongly constrained by $K - \bar{K}$ mixing. 

Trine, Wiesenfeldt, Westhoff 2009
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Similar constraints can be found from $\mu \rightarrow e\gamma$. Ko, Park, Yamaguchi 2008; Borzumati, Yamashita 2009; Girrbach, Mertens, UN, Wiesenfeldt 2009.
Chang-Masiero-Murayama model

We have considered $B_s - \overline{B}_s$ mixing, $b \rightarrow s\gamma$, $\tau \rightarrow \mu\gamma$, vacuum stability bounds, lower bounds on sparticle masses and the mass of the lightest Higgs boson. The analysis involves 7 parameters in addition to those of the Standard Model.

Generic results: Largest effect in $B_s - \overline{B}_s$ mixing tension with $M_h \geq 114$ GeV

J. Girrbach, S. Jäger, M. Knopf, W. Martens, UN, C. Scherrer, S. Wiesenfeldt

1101.6047
Methodology:

Input:

- squark masses $M_{\tilde{u}}, M_{\tilde{d}}$ of right-handed up and down squarks,
- trilinear term $a_{1}^{d}$ of first generation,
- gluino mass $m_{\tilde{g}_{3}}$,
- $\arg \mu$,
- $\tan \beta$
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RG evolution from $M_{ew}$ to $M_{Pl}$: find universal soft terms $a_0, m_0, m_{\tilde{g}}$ and $D$. 
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Repeat RG evolution $M_{\text{ew}} \rightarrow M_{\text{Pl}} \rightarrow M_{\text{ew}}$: find all particle masses and MSSM couplings
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Repeat RG evolution $M_{\text{ew}} \rightarrow M_{\text{Pl}} \rightarrow M_{\text{ew}}$: find all particle masses and MSSM couplings

adjust CP phase $\xi$ to approximate experimental $\Delta_s$ best.
$m_{g_3} = 500 \text{ GeV, } \mu > 0, \tan \beta = 6$

Black: negative soft masses
Gray blue: excluded by $\tau \to \mu \gamma$
Medium blue: excluded by $b \to s\gamma$
Dark blue: excluded by $B_s - \bar{B}_s$ mixing
Green: allowed

solid lines: $10^4 \cdot Br(b \to s\gamma)$; dashed lines: $10^8 \cdot Br(\tau \to \mu \gamma)$.
$m_{\tilde{g}_3} = 500 \text{ GeV}, \mu > 0, \tan \beta = 6$

gray labels: $\phi_s$ in degrees
white labels: $M_h$. 
It is easy to accommodate the large values of $|\phi_s|$ seen in the data.

For $\tan \beta = 3$ the bound $M_h \geq 114 \text{ GeV}$ is violated.
Origin of the **SUSY flavor problem**: Misalignment of squark mass matrices with Yukawa matrices. Unorthodox solution: Set $Y_{ij}^u$ and $Y_{ij}^d$ to zero, except for $(i, j) = (3, 3)$.

$$\Rightarrow \text{ No flavor violation from } Y_{ij}^{u,d} \text{ and } V_{\text{CKM}} = 1.$$
Radiative Flavor Violation

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$V_{\text{CKM}} \neq 1$ is then generated radiatively, through finite squark-gluino loops.

$\Rightarrow$ **SUSY-breaking is the origin of flavor.**
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$\Rightarrow$ SUSY-breaking is the origin of flavor.

Radiative flavor violation: S. Weinberg 1972

flavor from soft SUSY terms:

W. Buchmüller, D. Wyler 1983,
F. Borzumati, G.R. Farrar,
N. Polonsky, S.D. Thomas 1998, 1999
J. Ferrandis, N. Haba 2004
Today:

Strong constraints from FCNCs probed at B factories.
Today:

Strong constraints from FCNCs probed at B factories.

**But:** Radiative flavor violation in the MSSM is still viable, albeit only with $A_{ij}^d$ and $A_{ij}^u$ entering

$$M_{ij}^{\tilde{d}}_{LR} = A_{ij}^d v_d + \delta_{i3} \delta_{j3} y_{b\mu} v_u, \quad M_{ij}^{\tilde{u}}_{LR} = A_{ij}^u v_u + \delta_{i3} \delta_{j3} y_{t\mu} v_d.$$ 

Requires heavy sparticles, with squark masses around or above 1 TeV.

Andreas Crivellin, UN, PRD 79 (2009) 035018
Corrections to Yukawa couplings from $A_{ij}^d$:
If all flavor violation is generated from $A^d_{ij}$, there are correlated effects in $B(B_S \to \mu^+\mu^-)$ and $B_s - \bar{B}_s$ mixing:

Here $\tan \beta = 11$ and $M_{H^0} \simeq M_{A^0} = 400$ GeV. $V_{23}^R$ parametrizes the $s_R \to b_L$ self-energy as $V_{23}^R \equiv \Sigma(s_R \to b_L)/m_b$.

Crivellin, Hofer, UN, Scherer, 1105.2818
The DØ result for the dimuon asymmetry in $B_s$ decays supports the hints for $\phi_s < 0$ seen in $B_s \rightarrow J/\psi \phi$ data of DØ, CDF and LHCb.
Conclusions

• The DØ result for the dimuon asymmetry in $B_s$ decays supports the hints for $\phi_s < 0$ seen in $B_s \rightarrow J/\psi \phi$ data of DØ, CDF and LHCb.

• A global fit to the UT indeed shows a slight preference for a new CP phase $\phi_d^\Delta < 0$, driven by $B(B^+ \rightarrow \tau^+ \nu_\tau)$ (and possibly $\epsilon_K$). In a simultaneously global fit to the UT and the $B_s - \bar{B}_s$ mixing complex a plausible picture of new CP-violating physics emerges.
• Large CP-violating contributions to $B_s - \bar{B}_s$ mixing are possible in supersymmetry without violating constraints from other FCNC processes. If confirmed the DØ/CDF results imply physics beyond the CMSSM and mSUGRA. We need “controlled” deviations from minimal flavor violation.
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- Models of GUT flavor physics with $\tilde{b}_R - \tilde{s}_R$ mixing driven by the atmospheric neutrino mixing angle can explain the Tevatron data on $B_s - \bar{B}_s$ mixing without conflicting with $b \to s\gamma$ and $\tau \to \mu\gamma$. 
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- The MSSM with radiative flavor violation permits sizable effects in $B(B_s \to \mu^+\mu^-)$ and $B_s - \overline{B}_s$ mixing, but requires $\mathcal{O}(\text{TeV})$ squark and gluino masses.
A pinch of new physics in $B - \overline{B}$ mixing?