Unitary Triangle and New Physics

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The fermion mass puzzle

Fermion masses

(large angle MSW)

$\nu_1 \rightarrow \nu_2 \rightarrow \nu_3$

$\begin{align*}
\mu & \quad \text{MeV} \\
\tau & \quad \text{MeV} \\
\mu & \quad \text{GeV} \\
\tau & \quad \text{GeV} \\
\end{align*}$
Smallness and Hierarchy

\[ Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5} \]
\[ Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4} \]
\[ Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_\nu \sim 10^{-6} \]
\[ |V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\text{KM}} \sim 1 \]

- For comparison: \( g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1 \)
- The SM flavor parameters have structure:
  smallness and hierarchy
- Why? = The SM flavor puzzle

Nir
SM success

Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism (Nir)
UT tensions

- Recent theoretical improvements in $\epsilon_K$ expose some tensions in the UT analysis [Lunghi & Soni, Buras & Guadagnoli]
- Look at $\epsilon_K, S_{\psi K_S} (\sin 2\beta), \Delta M_d/\Delta M_s$ in the $R_b-\gamma$ plane
- $R_b, \gamma$ can be obtained from tree-level processes

Altmannshofer et al. ’09
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Possible solutions:

1. +24% NP effect in $\epsilon_K$
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2. $-6.5^\circ$ NP phase in $B_d$ mixing

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- $R_b$, $\gamma$ can be obtained from tree-level processes

Possible solutions:

1. +24% NP effect in $\epsilon_K$
2. $-6.5^\circ$ NP phase in $B_d$ mixing
3. $-22\%$ NP effect in $\Delta M_d/\Delta M_s$ (requiring $\alpha \sim 74^\circ$)

Altmannshofer et al. ’09
\[ \sin 2\beta_{\text{eff}} \] tensions

- In the SM, mixing-induced CP asymmetries in \( B_d \to \psi K_S, \phi K_S, \eta' K_S \) all \( \approx \sin 2\beta \)
- \( B_d \to \psi K_S \) dominated by tree level, \( \phi K_S \) and \( \eta' K_S \) are loop-induced

Data indicate \( S_{\phi K_S} < S_{\eta' K_S} < S_{\psi K_S} \)

\[ \sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1\text{eff}}) \]

[adapted from HFAG]

New physics in the decay amplitudes?

Can only be resolved at SuperB
CPV in $B_s$ mixing

\[ S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s}) \]

\[ A_{SL}^q \equiv \frac{\Gamma(\bar{B}_q \to l^+ X) - \Gamma(B_q \to l^- X)}{\Gamma(\bar{B}_q \to l^+ X) + \Gamma(B_q \to l^- X)} \]

New Physics in the $B_s$ mixing phase?
Motivation:

- **Baryogenesis** requires extra sources of CPV
- The QCD $\bar{\theta}$-term $\mathcal{L}_{CP} = \bar{\theta} \frac{\alpha_s}{8\pi} G \tilde{G}$ is a CPV source beyond the CKM
- Most UV completion of the SM have many CPV sources
Where to look for **New Physics** at the low energy?

- **Processes very suppressed or even forbidden** in the SM
  - FCNC processes ($\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, B_{s,d}^0 \rightarrow \mu^+\mu^-, K \rightarrow \pi\nu\bar{\nu}$)
  - CPV effects in the electron/neutron EDMs, $d_e, n...$
  - FCNC & CPV in $B_{s,d}$ decay/mixing & $D$ mixing amplitudes

- **Processes predicted with high precision** in the SM
  - EWPO as $\Delta\rho, (g - 2)_\mu....$
  - LU in $R_{M}^{e/\mu} = \Gamma(K(\pi) \rightarrow e\nu)/\Gamma(K(\pi) \rightarrow \mu\nu)$
### Flavour Matrix

<table>
<thead>
<tr>
<th>ELECT ROWEAK STRUCTURE</th>
<th>FLAVOUR COUPLING</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔF=2 box</td>
<td></td>
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<tr>
<td>4-quark ops.</td>
<td></td>
</tr>
<tr>
<td>gluon penguin</td>
<td>$A_{CP}(B_d \to \phi K)$</td>
</tr>
<tr>
<td>$[\Gamma, \Delta \Gamma_{CP}](B \to X_s \gamma)$</td>
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<td>$A_{FB}(B \to X_s \Gamma)$</td>
<td></td>
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<tr>
<td>$[\Gamma, \Delta \Gamma_{CP}](B \to X_s \Gamma)$</td>
<td></td>
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<td>$A_{FB}(B \to \rho/\pi \Gamma)$</td>
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SM vs. SUSY flavour problems

Flavour violation is highly non-generic already in the SM!

The two problems should be related!

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**Minimal Flavour Violation (MFV)**

- Yukawa couplings are the only sources of flavour violation
- Effective theory
- Pragmatic approach
- Pessimistic phenomenology

**Flavour Models**

- Flavour structure of Yukawa couplings and soft terms generated by spontaneous breaking of a flavour symmetry
- Ambitious approach
- Diverse phenomenology
Minimal Flavour Violation

- SM without Yukawa interactions: $SU(3)^5$ global flavour symmetry

$$SU(3)_u \otimes SU(3)_d \otimes SU(3)_Q \otimes SU(3)_e \otimes SU(3)_L$$

- Yukawa interactions break this symmetry

- Proposal for any New Physics model:

  Yukawa structures as the only sources of flavour violation

  $\Downarrow$

  Minimal Flavour Violation

  MFV allows for new “flavour blind” CPV phases!

Altmannshofer, Buras and P.P., ’08
Flavor blind MSSM $\approx$ MFV + CPV

- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta', K_S}$ can simultaneously be brought in agreement with the data
- Sizeable and correlated effects in $A_{CP}^{b\to s\nu}$ $\approx$ 1% -- 6%
- Lower bounds on the electron and neutron EDMs at the level of $d_{e,n} \gtrsim 10^{-26}$ ecm
- Large and correlated effects in the CP asymmetries in $B \to K^* \mu^+ \mu^-$ (WA, Ball, Bharucha, Buras, Straub, Wick)

- The leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and $\epsilon_K$
- In particular: $0.03 < S_{\psi\phi} < 0.05$

A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM
Phenomenology of the flavor blind MSSM

1. Kaon mixing
   - The mixing amplitude $M_{12}^K$ has no sensitivity to the new flavor blind phases.
   - Still, $\epsilon_K \propto \text{Im}(M_{12}^K)$ can get a positive NP contribution up to 15%.
   - But only for a very light SUSY spectrum: $\mu, m_{\tilde{t}_1} \approx 200\text{GeV}$.

2. $B_d$ and $B_s$ mixing
   - Leading NP contributions to $M_{12}^{d,s}$ are insensitive to the new phases of a FBMSSM. (at least for moderate $\tan \beta$ ...)
   - For large $\tan \beta$, the constraint from $b \rightarrow s\gamma$ does not allow for sizeable effects.
   - $S_{\psi K_S}$ and $S_{\psi \phi}$ are SM like ($S_{\psi \phi} \approx 0.03 - 0.05$).
Main idea: hierarchies in Yukawa couplings generated by spontaneous breakdown of flavour symmetry (horizontal symmetry, family symmetry)

- Generalization of the Froggat-Nielsen mechanism
- Yukawa hierarchies explained by different powers of small $\epsilon$:

$$ Y_{ij} \propto \left( \frac{\langle \phi \rangle}{M} \right)^{(a_i + b_j)} = \epsilon^{(a_i + b_j)} $$

- Possible to relate Yukawa matrices and sfermion mass matrices/trilinear couplings

SUSY flavour models can explain the origin of the hierarchies in the Yukawa couplings and solve the SUSY flavour problem

- Many different viable models exist, with abelian or non-abelian flavour symmetries
Abelian vs. non-Abelian flavour models

Abelian vs. Non-abelian

- In most non-abelian models, 1st & 2nd generation sfermions are approximately degenerate
  - Suppressed contributions to $1 \leftrightarrow 2$ transitions, in particular $D^0 - \bar{D}^0$ mixing
- In abelian models, sfermions of different generations need not be degenerate
  - $O(1)$ 1-2 mass splitting leads to $O(\lambda) (\delta_{u}^{LL})_{12}$ in the SCKM basis
  - Large effects in $D^0 - \bar{D}^0$ mixing

Chirality structure of flavour violating terms

- Different flavour symmetries lead to different patterns of flavour violation
- Mass insertions: $M_d^2 = \text{diag} (\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta_{d}^{LL} & \delta_{d}^{LR} \\ \delta_{d}^{RL} & \delta_{d}^{RR} \end{pmatrix}$
- $\delta^{LL}, \delta^{RR}, \delta^{LR}$ fixed by the flavour symmetry (up to $O(1)$ factors)
Examples of flavour models

### 4 representative flavour models with different chirality structures in the $\tilde{d}$ sector:

<table>
<thead>
<tr>
<th>Model</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC model</td>
<td>[Agashe, Carone]</td>
</tr>
<tr>
<td>$U(1)$</td>
<td>Large, $O(1)$ RR mass insertions</td>
</tr>
<tr>
<td>AKM model</td>
<td>[Antusch, King, Malinsky]</td>
</tr>
<tr>
<td>$SU(3)$</td>
<td>Only CKM-like RR mass insertions</td>
</tr>
<tr>
<td>RVV model</td>
<td>[Ross, Vetasco-Sevilla, Vives]</td>
</tr>
<tr>
<td>$SU(3)$</td>
<td>CKM-like LL &amp; RR mass insertions</td>
</tr>
<tr>
<td>$\delta LL$ model</td>
<td>[e.g. Hall, Murayama]</td>
</tr>
<tr>
<td>$(S_3)^3$</td>
<td>Only CKM-like LL mass insertions</td>
</tr>
</tbody>
</table>

\[
\delta_d^{LL} \sim \begin{pmatrix}
\lambda^2 & 0 & 0 \\
0 & \lambda^2 & 0 \\
0 & 0 & \lambda^2
\end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix}
0 & 0 & 1 \\
0 & 1 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

\[
\delta_d^{LL} \sim \begin{pmatrix}
\lambda^3 & 0 & 0 \\
0 & \lambda^2 & 0 \\
0 & 0 & \lambda^2
\end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix}
\lambda^3 & \lambda^3 & \lambda^3 \\
\lambda^3 & \lambda^2 & \lambda^2 \\
\lambda^3 & \lambda^2 & \lambda^2
\end{pmatrix}
\]

\[
\delta_d^{LL} \sim \begin{pmatrix}
\lambda^5 & 0 & 0 \\
\lambda^5 & \lambda^2 & 0 \\
\lambda^5 & \lambda^2 & \lambda^2
\end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

Altmannshofer et al. ’09
\( Br(B_s \rightarrow \mu^+\mu^-) \) vs. \( S_{\psi\phi} \)

- Both observables can deviate significantly from the SM in all 3 models
- Large \( S_{\psi\phi} \) \( \Rightarrow \) large \( Br(B_s \rightarrow \mu^+\mu^-) \) in the AC and AKM models
- Correlation arises from dominance of Higgs penguin contributions

**AC**

![AC Diagram]

**AKM**

![AKM Diagram]

**RVV**

![RVV Diagram]

- **Orange points**: UT tension solved through contribution to \( \Delta M_d / \Delta M_s \)
- **Blue points**: UT tension solved through contribution to \( \epsilon_K \)
- **Scan ranges**: \( m_0 < 2 \text{ TeV}, M_{1/2} < 1 \text{ TeV}, |A_0| < 3m_0, 5 < \tan \beta < 55, O(1) \) parameters varied within \([1/2, 2]\)
$S_\phi K_S$ vs. $S_\psi \phi$

- In the AC model, both $S_\phi K_S$ and $S_\psi \phi$ can have large effects, but a simultaneous enhancement of $S_\psi \phi$ and suppression of $S_\phi K_S$ (as indicated by the data) is impossible.
- $S_\phi K_S$ nearly SM-like in AKM and RVV models.

**AC**

**AKM**

**RVV**

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- **Blue points**: UT tension solved through contribution to $\epsilon_K$.
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Model with purely left-handed currents

Pattern of NP effects in the $\delta LL$ model:

- No large effects in $S_{\psi \phi}$
- Large, correlated effects in $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{CP}(b \to s \gamma)$, $\langle A_{7,8} \rangle$
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \to K^* \ell^+ \ell^-$

- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan \beta < 55$, $O(1)$ parameters varied within $[\frac{1}{2}, 2]$
$Br(B_s \rightarrow \mu^+ \mu^-)$ vs. $Br(B_d \rightarrow \mu^+ \mu^-)$

Abelian (AC)

Non abelian (RVV)

$Br(B_s \rightarrow \mu^+ \mu^-)/Br(B_d \rightarrow \mu^+ \mu^-) = |V_{ts}/V_{td}|^2$ in MFV models
CPV in D-physics

\[ \langle D^0 | H_{\text{eff}} | \bar{D}^0 \rangle = M_{12} - \frac{i}{2} \Gamma_{12}, \quad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \]

\[ \frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}}} , \quad \phi = \text{Arg}(q/p) \]

\[ x = \frac{\Delta M_D}{\Gamma} = 2\tau \text{Re} \left[ \frac{q}{p} (M_{12} - \frac{i}{2} \Gamma_{12}) \right] \]

\[ y = \frac{\Delta \Gamma}{2\Gamma} = -2\tau \text{Im} \left[ \frac{q}{p} (M_{12} - \frac{i}{2} \Gamma_{12}) \right] \]

\[ S_f = 2\Delta Y_f = \frac{1}{\Gamma_D} \left( \hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f} \right) \]

\[ \eta_{f}^{\text{CP}} S_f = x \left( \frac{|q|}{|p|} + \frac{|p|}{|q|} \right) \sin \phi - y \left( \frac{|q|}{|p|} - \frac{|p|}{|q|} \right) \cos \phi \]

\[ a_{SL} = \frac{\Gamma(D^0 \to K^+\ell^-\nu) - \Gamma(\bar{D}^0 \to K^-\ell^+\nu)}{\Gamma(D^0 \to K^+\ell^-\nu) + \Gamma(\bar{D}^0 \to K^-\ell^+\nu)} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4} \]
CPV in D-physics vs. neutron EDM in SUSY

FIG. 3: Correlations between $d_n$ and $S_f$ (left), $d_n$ and $a_{SL}$ (middle) and $a_{SL}$ and $S_f$ (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from $\phi$. Dashed lines stand for the allowed range (18) for $S_f$.

FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.
### DNA-Flavour Test

<table>
<thead>
<tr>
<th></th>
<th>GMSSM</th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>$\delta LL$</th>
<th>FBMSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\phi K_s}$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★</td>
<td></td>
<td>★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$A_{CP} (B \to X_s \gamma)$</td>
<td>★★★★</td>
<td></td>
<td>★★</td>
<td></td>
<td>★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$B \to K^{(*)} \nu \bar{\nu}$</td>
<td>★★</td>
<td>★★★★</td>
<td></td>
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<td>★★★</td>
<td>★★★★</td>
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<tr>
<td>$\tau \to \mu \gamma$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
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<td>★★★</td>
<td>★★★★</td>
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<tr>
<td>$D^0 - \bar{D}^0$</td>
<td>★★★★</td>
<td>★★★★</td>
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<tr>
<td>$A_{7,8} (B \to K^+ \mu^+ \mu^-)$</td>
<td>★★★★</td>
<td></td>
<td>★★★★</td>
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<tr>
<td>$A_9 (B \to K^+ \mu^+ \mu^-)$</td>
<td>★★★★</td>
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<td>★★★★</td>
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<tr>
<td>$S_{\psi \phi}$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
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<tr>
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<td>★★★★</td>
<td>★★★★</td>
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<td></td>
<td>★★★</td>
<td>★★★★</td>
</tr>
</tbody>
</table>

- $\epsilon_K$
- $K^+ \to \pi^+ \nu \bar{\nu}$
- $K_L \to \pi^0 \nu \bar{\nu}$
- $\mu \to e \gamma$
- $\mu + N \to e + N$
- $d_n$
- $d_e$
- $(g - 2)_\mu$

**Altmannshofer et al. ’09**
Isidori’s view

**Flavour physics in the LHC era**

**LHC** [high p_T]

A unique effort toward the high-energy frontier

[to determine the energy scale of NP]

**Flavour physics**

- Improved CKM fits
- Rare B decays
- CPV in the Bs system
- Universality tests in B & K
- Rare K decays
- LFV in $\mu$ & $\tau$ decays
- EDMs
- $g-2$

A collective effort toward the high-intensity frontier

[to determine the flavour structure of NP]
Masiero’s view

DM - FLAVOR
for DISCOVERY
and/or FUND. TH.
RECONSTRUCTION

A MAJOR LEAP AHEAD IS NEEDED

LHC

NEW PHYSICS AT THE ELW SCALE

DARK MATTER

m_x, n_x, \sigma_x, ... LINKED TO COSMOLOGICAL EVOLUTION

"LOW ENERGY" PRECISION PHYSICS

FCNC, CP \neq, (g-2), (\beta\beta)_{0\gamma\gamma}

Possible interplay with dynamical DE