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SUSY 2005, IPPP Durham, July 23, 2005

* “Implications of current and future $b$-data for (weak scale) SUSY ”

Thanks to HFAG, Zoltan Ligeti, Guy Raz, Salim Safir for input

Non-CP observables/rare decays → plenary talk by M. Misiak (Monday)
Lepton Flavor violation → plenary talk by A. Brignole (after this talk)

SM=Standard Model, NP=New Physics, EWKS=electroweak symmetry breaking, FCNC=Flavor changing neutral currents
SM tests with indirect processes

indirect loop processes:

\[ \mathcal{L}_{\text{eff}} = \sum_i c_i^{(n)} \frac{O_i^{(n)}}{\Lambda^n} \]

\[ c_i^{(n)} \leftrightarrow f(m_j, g_l, \ldots; \varphi_{\text{CKM}}, \varphi_m, \delta_n) \]

\[ \Lambda \gtrsim m_W \text{ scale of New Physics} \]

no competition from large SM tree contributions
complement collider searches

FCNC: sensitivity to SM and NP phases \( \varphi \) and flavor-breaking couplings \( \delta \)

MFV = no more flavor/CP violation than in SM, i.e. in Yukawas (CKM)

\( U(3)^5 \) symmetry only broken by “Y” spurion fields; RGE invariant
Flavor breaking in SUSY

superpotential leads to CKM-type flavor-breaking (with unbroken R-parity)

\[ -\mathcal{L}_{\text{soft}} \supset \tilde{Q}^\dagger m_Q^2 \tilde{Q} + \tilde{U}^\dagger m_U^2 \tilde{U} + \tilde{D}^\dagger m_D^2 \tilde{D} + A_U \tilde{Q} H_U \tilde{U} + A_D \tilde{Q} H_D \tilde{D} \]

squark masses (\textit{A-terms}) : \( 3 \times 3 \) hermitean (complex) matrices

super-CKM basis: quarks are mass eigenstates, but squarks not UNLESS

\[ m_{Q,D,U}^2 \propto 1 \text{ and } A_{U,D} \propto Y_{U,D} \quad (1) \]

beyond (1) \( \rightarrow \) large \# of new sources of flavor/CP violation

e.g. tree level FCNC \( \tilde{g}\tilde{q}_i\tilde{q}_j \), mass insertions \( \delta_{i,j}^{U,D} \equiv \Delta m_{i,j}^{2U,D}/m_{\text{diag}}^{2U,D} \)

(1) realized in GMSB, AMSB, CMSSM (RGE induced effects tiny)

beyond MFV terms in \( b \rightarrow s \) motivated from GUTs from large \( \nu_\mu - \nu_\tau \)

oscillations \( \rightarrow \) sizeable effects in \( B_s - \bar{B}_s \)-mixing \( \text{hep-ph/0212180, 0212397} \)
models of EWKSB with NP @ TeV

reach in indirect signals

rare $b, c, K, \tau$-decays, mixing, EDMs, $g-2$
depends on beyond the SM flavor/CP violation (minimal=CKM ?), large
parameters e.g. $\tan \beta$ and theor. and exp. uncertainties

Fig from hep-ph/0207121
Plan of the talk

- Introduction: SUSY effects in $b$-physics

- Searching for BSM phases in $b \rightarrow s$: “$\sin 2\beta$” measurements

- Recent and future SM tests from $b \rightarrow s\gamma$, $b \rightarrow s\ell^+\ell^-$ processes

- Flavor violation in models beyond the minimal model
  - R-parity violating effects in double radiative decays
  - light $A^0$ in NMSSM at large $\tan \beta$

- Outlook

*in this talk $\beta$ denotes the phase of $B\bar{B}$-mixing, i.e. $\beta_{\text{eff}}$
Time-dependent CP asymmetries in $b \to s\bar{q}q$ decays

SM+MFV: $-\eta_{CP} \sin 2\beta\left((\bar{s}s)K_S\right) = \sin 2\beta\left((\bar{c}c)K_S\right) + \left| \frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \right| \cdot \#$

$\mathcal{O}(\lambda^2)$

$\sum \left| \sin(2\beta_{\text{eff}}) \right| / \sin(2\phi_{\text{eff}})$

since Moriond: $\sim 1\sigma$ shifts in $\bar{c}c$, $\Phi$, larger ones in $K_S^3$, $f_0$; $\eta'$ off by $2.3\sigma$

better agreement between Belle and BaBar
\[ \Delta S = -\eta_f S_f - \sin 2\beta \]

| \( f \)       | \( \Delta S^{QCDF@NLO}_{SM} \) | \( \Delta S^{QCDF@LO}_{SM} \) | \( |\Delta S^{SU(3)+}_{SM}| \) | \( S_f \) LP’05  | \( C_f \) LP’05 |
|---------------|-------------------------------|-------------------------------|-----------------------------|----------------|----------------|
| \( \Phi K^0 \) | 0.01 \ldots 0.03              | 0.02                          | \( \lesssim 0.3 \)         | 0.47 \pm 0.19 | -0.09 \pm 0.14|
| \( \eta' K^0 \) | 0 \ldots 0.02                 | -0.01 \ldots 0.02             | \( \lesssim 0.15 \)        | 0.48 \pm 0.09 | -0.08 \pm 0.07|
| \( \pi^0 K_S \) | 0.03 \ldots 0.12              | 0.03 \ldots 0.10              | \( \lesssim 0.2 \)         | 0.31 \pm 0.26 | -0.02 \pm 0.13|
| \( \omega K_S \) | 0.05 \ldots 0.22              | 0.05 \ldots 0.25              | -                           | 0.63 \pm 0.30 | -0.44 \pm 0.23|

LO captures central value and uncertainty of full NLO calc. of \( \Delta S_f \)

for all above modes: QCD factorization predicts \( \Delta S_f > 0 \), experimental shifts \( < 0 \); no significant \( C_f \neq 0 \)

ultimately more precision needed; all exp. errors \( \lesssim 0.1 \) only by time of super-\( b \)-factory  

\[ \text{hep-ph/0503261} \]
Pattern of NP in $b \rightarrow s$ Penguin modes

generic NP scenarios with one additional phase, use QCDF @ LO \cite{hep-ph/0503151}

\begin{itemize}
  \item SM
  \item Z–penguins
  \item KK–gluons
  \item non–SM $C_{8g}$
\end{itemize}

input: $S_{\pi^0 K_S} = 0.34$ and maximal NP amplitude ok with other data
predict $S_f$ for: $\blacktriangledown = \Phi$, $\blacktriangle = \eta'$, $\blacksquare = \eta$, $\times = \omega$, $\blacktriangleup = \rho$

goal: identify type of NP from characteristic SM departure

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Fit generic NP scenarios to current data

\[ A = A_{SM} + A_{NP}; \quad A_{NP} \propto \epsilon_i e^{i \vartheta_i} \]

\[ \chi^2 \text{-fit to } b \to s \text{ penguin data} \]

\begin{align*}
\varepsilon_z & \quad \vartheta_z \\
\varepsilon_k & \quad \vartheta_k \\
\varepsilon_g & \quad \vartheta_g \\
\varepsilon_9 & \quad \vartheta_9
\end{align*}

black, dark grey, light grey regions: probability \( > 0.32, 0.046, 0.0027 \)

IFF \( A_{NP} \gg A_{SM} \) 4-fold solution \( \sin 2(\beta + \vartheta) \approx 0.4 \) (with \( \cos 2\beta > 0 \))

NP amplitudes can be larger if no phase \( \vartheta = 0, \pi \)

all 3 scenarios have solution, which is more favored than SM \( (\epsilon_i = 0) \)
assume gluino loops are dominant: $\delta_{23}^D$, LL, LR, RL, RR, complex

impose bounds from $b \to s\gamma$, $b \to s\ell\ell$ (pre LP05 data)
### Some (further) SM tests with $b$-physics

<table>
<thead>
<tr>
<th></th>
<th>experiment</th>
<th>SM</th>
<th>comments</th>
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<tbody>
<tr>
<td>$a_{CP}(b \to s\gamma)$</td>
<td>$0.4 \pm 3.6%$</td>
<td>$0.42 \pm 0.17%$_{hep-ph/0312260}</td>
<td>CPX in $bs\gamma, g$</td>
</tr>
<tr>
<td>$a_{CP}(b \to d/s\gamma)$</td>
<td>$-0.110 \pm 0.116$_{BaBar'05}</td>
<td>$10^{-9}$_{hep-ph/0312260}</td>
<td>test MFV</td>
</tr>
<tr>
<td>$S_{K_S\pi^0\gamma}$</td>
<td>$0.00 \pm 0.28$_{Belle/BaBar'05}</td>
<td>$-2m_s/m_b$</td>
<td>V+A FCNCs</td>
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<tr>
<td>$B(B \to X_s g)$</td>
<td>$&lt; 9%$ CLEO'97</td>
<td>$5.0 \pm 1.0 \cdot 10^{-3}$</td>
<td>NP in $bsg$</td>
</tr>
<tr>
<td>$B(B \to X_s \bar{\mu}\mu)$</td>
<td>$4.3 \pm 1.2 \cdot 10^{-6}$</td>
<td>$4.3 \pm 0.7 \cdot 10^{-6}$</td>
<td>$q^2$-spectra CPX</td>
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<tr>
<td>$a_{CP}(B \to X_s \bar{\ell}\ell)$</td>
<td>$-0.22 \pm 0.26$</td>
<td>$-0.2 \pm 0.2$%_{hep-ph/9812267}</td>
<td>CPX in $bsZ$</td>
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<tr>
<td>$A_{FB}^C(B \to K^*\ell\ell)$</td>
<td>$-\text{sym.}$</td>
<td>$\lesssim 10^{-3}$_{hep-ph/0006136}</td>
<td>non-SM Higgs $O(10)$ from SM</td>
</tr>
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<td>$R_K \mu\mu$ vs. $ee$</td>
<td>$1.06 \pm 0.48$_{BaBar'05}</td>
<td>$1+\mathcal{O}(m^{2}_\mu/m^{2}<em>b)$</em>{hep-ph/0310219}</td>
<td>$O(100)$ from SM</td>
</tr>
<tr>
<td>$B(B \to K\nu\bar{\nu})$</td>
<td>$&lt; 3.6 \cdot 10^{-5}$_{Belle'05}</td>
<td>$3.8^{+1.2}_{-0.6} \cdot 10^{-6}$</td>
<td>$O(10^5)$ from SM hadron colliders</td>
</tr>
<tr>
<td>$B(B_s \to \mu^+\mu^-)$</td>
<td>$&lt; 5.8 \cdot 10^{-7}$</td>
<td>$3.2 \pm 1.5 \cdot 10^{-9}$</td>
<td></td>
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<tr>
<td>$B(B_s \to \tau^+\tau^-)$</td>
<td>$&lt; \mathcal{O}(5%)$</td>
<td>$7.2 \pm 1.1 \cdot 10^{-7}$</td>
<td></td>
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<tr>
<td>$\Delta m_s$</td>
<td>$&gt; 15/\text{ps}$</td>
<td>$(15 - 22)/\text{ps}$</td>
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Impact of $b \rightarrow s\ell^+\ell^-$ beyond MFV, perspectives

$\mathcal{B}(b \rightarrow s\ell^+\ell^-)$: best bound on $Z$-penguins $\bar{s}Zb$-coupling $\sim C_{10} \lesssim 2 \times$ SM order 1 effects in $C_{10}$ from $\delta_{23}^U$ possible (LR and LL) hep-ph/9906286,0006136

great NP sensitivity in $q^2$-spectra in $b \rightarrow s\ell^+\ell^-$; asy # forward - # backward $\ell^+$ in dilepton CMS w.r.t. $\bar{B}$ needs tagging $A_{FB}^{SM} + \tilde{A}_{FB}^{SM} \approx 0$

$A_{FB}(\hat{s}) \sim \text{Re} \left[ C_{10}^* (C_{eff}^{7f} + \beta(\hat{s}) C_{9}^{eff}) \right]$ also $B \rightarrow K^*\ell^+\ell^- \rightarrow$ Belle‘04

shape sensitive to sign $C_7$ (no zero for $C_7 > 0$); $A_{FB} \propto C_{10}$; flat possible zero allows precision test of SM $\hat{S}_{SM}^{NNLL} = 0.162 \pm 0.002(8)$ hep-ph/0208088,0209006
NP in $bs\gamma + \gamma$ tightly constrained by $\mathcal{B}(B \to X_s\gamma)$, but 1PI has room

[Diagram]

impact of 4-Fermi's is higher order in $b \to s\gamma$, lepton-loop down by $\alpha_{em}$

$b \to s\tau^+\tau^-$ essentially unconstrained $\mathcal{B}(B_s \to \tau^+\tau^-) < 5\%$ hep-ph/0411344

R-parity violation: biggest contribution from $\tilde{\nu}_\mu$ through $\lambda'_{232}\lambda_{233}$ hep-ph/0404152

RPV: $Br/Br_{SM}(B_s \to \gamma\gamma) \lesssim 16$ $Br/Br_{SM}(B \to X_s\gamma\gamma) \lesssim 5$

dataindependently: $Br/Br_{SM}(B \to K\gamma\gamma) \lesssim O(10)$ hep-ph/0411344

$\mathcal{B}^{L3}(B_s \to \gamma\gamma) < 1.48 \cdot 10^{-4} \approx 10^2 \cdot \mathcal{B}_{SM}(B_s \to \gamma\gamma)$
direct searches: \( h^0 \rightarrow A^0 A^0 \) open if \( 2m_{A^0} < m_{h^0} \)

can be VERY important for \( \mathcal{O}(1) \) \( h^0 A^0 A^0 \)-coupling

decay modes: \( A^0 \rightarrow \bar{b}b, \tau\tau, 3\pi \) or higher hadronic, \( \mu\mu, ee, \gamma\gamma \)

if \( A^0 \) very light and weakly coupled, it becomes missing energy

bounds from \( \Upsilon \)-decays, beam dump, astro physics \( m_{A^0} \gtrsim \mathcal{O}(100\text{MeV}) \) ok
NMSSM constraints from indirect signals

\[ W = Q Y_u H_u U + Q Y_d H_d D + L Y_e H_d E + \lambda H_d H_u N - \frac{1}{3} k N^3 \]

\( N \) : singlet

at large \( \tan \beta \): naturally light \( A_1^0 \), rad. stable

\[ b \rightarrow s A_1^0 \] transitions

bounds from \( B \rightarrow K A_1^0, K \rightarrow \pi A_1^0, \Upsilon(1s) \rightarrow \gamma A_1^0 \) decays

\( A_1^0 \) masses as low as \( \mathcal{O}(10\text{MeV}) \) viable \( \text{hep-ph/0404220} \)
**Light CP-odd $A^0$: further tests from $b$-physics**

- Improve bounds from radiative $\Upsilon$-decays or $B \to K^+\text{missing energy}$
- For $m_{\psi'} < m_{A^0_1} \lesssim m_B$: search for $A^0_1$ in $b \to s\tau^+\tau^-$ processes sensitivity e.g. $B(B \to X_s\tau^+\tau^-) \sim 10^{-3}$
- $B_s - \bar{B}_s$ mixing and $B_s \to \mu^+\mu^-$  
  CDF: $B(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-7}$
  in MSSM correlated
  in NMSSM: SM-like $\Delta m_s$ ($A^0_1$ contribution constrained by $\Delta m_d$), but not correlated with $B(B_s \to \mu^+\mu^-)$ hep-ph/0404220

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Fig adopted from hep-ph/0207241

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• indirect (loop) processes are unique probes of CP/flavor sector

• flavor experiments distinguish MFV vs. non-MFV; very different model-building; sensitivity to very high scales $\Lambda_{\text{SUSY}} \gg \Lambda_{\text{EWK}}$

• goal: measure ALL (flavor diagonal $\rightarrow$ direct searches and flavor breaking $\rightarrow$ FCNC) couplings/parameters precisely

• so far agreement with SM/CKM, “$\sin 2\beta$” data moved closer to MFV some hints ($\eta'K^0$); issue exciting and unsettled $\rightarrow$ higher precision

• many FCNC couplings only weakly or just un-constrained ..$\Delta m_s, \tau^\pm$,.. 

• scenarios beyond minimal MSSM+MFV: interplay between flavor physics and direct searches largely unexplored

• study correlations & pattern rather than individual observables
back up slides
Double radiative $b \rightarrow q\gamma\gamma$ decays, status

<table>
<thead>
<tr>
<th>modes</th>
<th>$\mathcal{B}_{SM}$</th>
<th>90 % C.L. bounds</th>
</tr>
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<tbody>
<tr>
<td>$B_d \rightarrow \gamma\gamma$</td>
<td>$3.1^{+6.4+1.0+1.0+1.3}_{-1.6-0.9-0.7-1.0} \cdot 10^{-8}$</td>
<td>$5.4 \cdot 10^{-6}$ \text{ Belle'05}</td>
</tr>
<tr>
<td>$B_s \rightarrow \gamma\gamma$</td>
<td>$1.2^{+2.5+0.3+0.3+0.01}_{-0.6-0.3-0.2-0.02} \cdot 10^{-6}$</td>
<td>$1.48 \cdot 10^{-4}$ \text{ L3}</td>
</tr>
<tr>
<td>$B \rightarrow X_s\gamma\gamma$</td>
<td>$(3.7 - 5.1) \cdot 10^{-7}$</td>
<td>-</td>
</tr>
<tr>
<td>$B \rightarrow K\gamma\gamma$</td>
<td>$(0.5 - 5.6) \cdot 10^{-7}$ \text{ A,B,D}</td>
<td>-</td>
</tr>
<tr>
<td>$B \rightarrow K^*\gamma\gamma$</td>
<td>few $\cdot 10^{-7}$ \text{ C,D}</td>
<td>-</td>
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A: Singer,Zhang'97 B: Choudhury etal'03 C: Choudhury etal'04 D: Hiller,Safir'04 (OPE for short-distance 1PR)

Note $\sum_{H=K,K^*} \mathcal{B}(B \rightarrow H\gamma\gamma) < \mathcal{B}(B \rightarrow X_s\gamma\gamma)$; semi-radiative decays suffer charmonium pollution $\eta_c, \chi$; $Br's$ depend on cuts

$B \rightarrow \gamma\gamma$ errors: $\lambda_B, f_B, \mu, \gamma$ Bosch,Buchalla '02
$b \to s \gamma, b \to s \ell^+ \ell^-$ decays

diagrams in SM

$$\mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i(\mu) O_i(\mu)$$

dipole operators $O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$

4-Fermi operators $O_8 \propto \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu}$

new physics in Wilson coefficients $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$ and/or new operators

model-independent analysis: $B_r$'s, $A_{CP}, A_{FB} = f(C_i) \to \text{fit!}$