Interplay

of Flavour and Collider Physics

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- Interplay of LHC and LC:
  Complementarity of discovery and precision machine

  $\Rightarrow$ LHC/LC study group

- However: LC will not be built before 2016 (optimistic!)

- Obvious question:
  What is the role of the flavour factories in this game?

- Experimental 'Roadmap' of flavour physics:

  - e^+e^--B-experiments:
    B factories (Babar,Belle) $\geq$ 1999, CLEO III $\geq$ 2000,
    Upgraded B factories, Super B factories $\geq$ 2010

  - Hadronic B-experiments:
    Tevatron II $\geq$ 2001, LHC (Atlas,CMS,LHCb) $\geq$ 2007,
    ((BTeV $\geq$ 2009))

  - Kaon-experiments:
    Kopio,BNL ($K_L \to \pi^0 \nu\bar{\nu}$), NA 48/3,CERN ($K^+ \to \pi^+ \nu\bar{\nu}$)
    $\geq$ 2010

Two Examples:

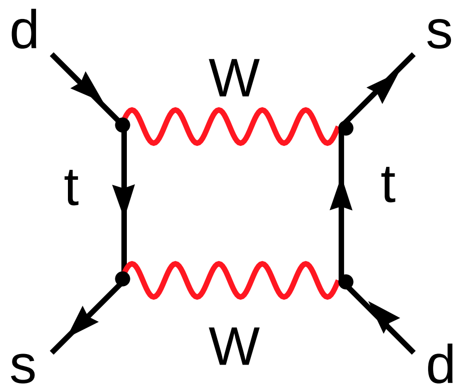
- Exploration of higher scales via rare decays

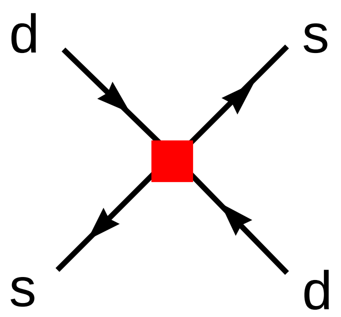
- Correlations between B and collider physics
  via squark mixing within Susy

Exploration of higher scales via flavour observables

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off-scale Λ
- $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2 \quad \Rightarrow \quad \Lambda > 100\,\text{TeV}$



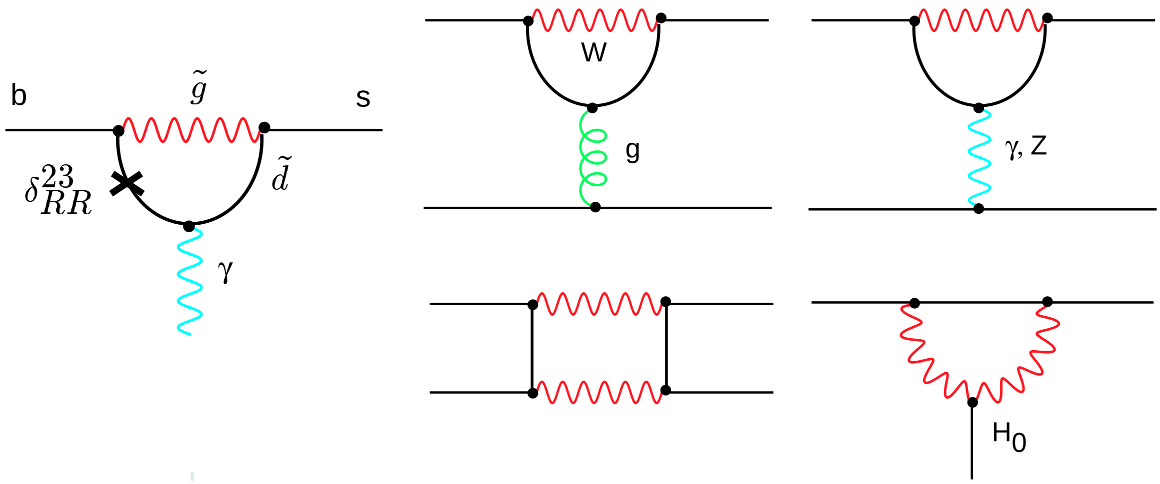


$\Rightarrow c^{SM}/M_W^2 \times (\bar{s}\, d)^2$ $\qquad$ $c^{New}/\Lambda^2 \times (\bar{s}\, d)^2$

- Natural stabilisation of Higgs boson mass $\Rightarrow \Lambda \sim 1\text{TeV}$
  i.e. supersymmetry, superpartner: $\Lambda_{SUSY} \precsim 1$ TeV
- Expectation:
  flavour mixing restricted by additional symmetries
  Rare decays and specific CP violating observables allow to analyse flavour symmetry breaking

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda} \mathcal{O}_i^{(5)} + \ldots$$

- Flavourblind elektroweak structure of $\mathcal{O}_i$:
  - connects various (theoretically clean !) observables:
  i.e. $A_{CP}(B_d \to \Phi K_S) \Leftrightarrow BR(B \to X_s\gamma)$

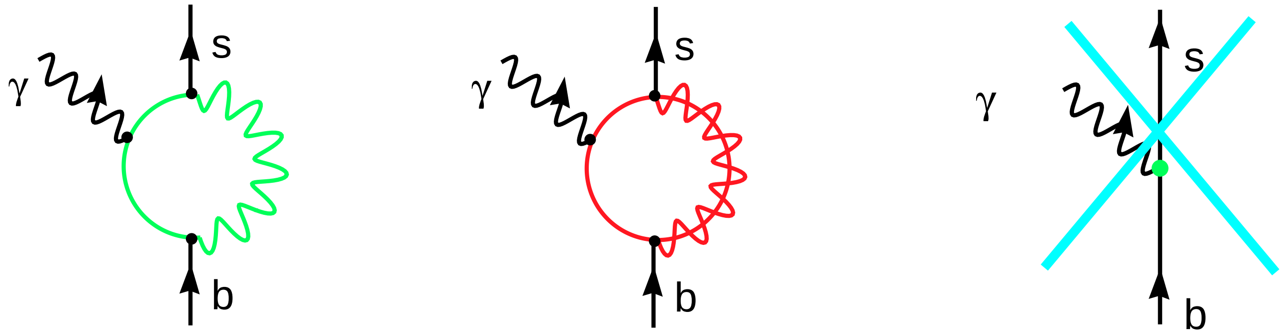


  - allows for model-independent analysis:

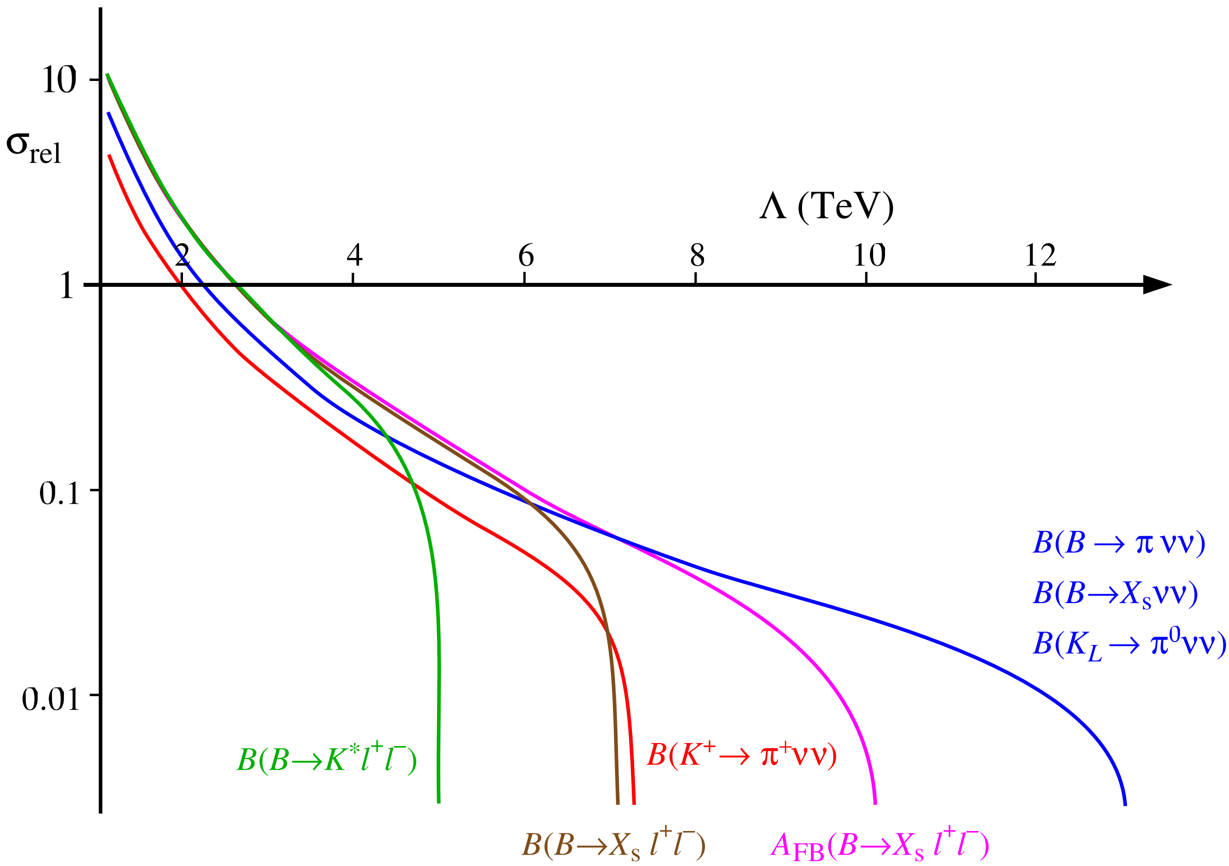
$$BR(B \to X_s\ell^+\ell^-), A_{FB}(B \to X_s\ell^+\ell^-), A_{CP}(B \to X_s\gamma),$$
$$BR(B \to \ell^+\ell^-), BR(K^+ \to \pi^+\nu\bar{\nu}), BR(B \to X_s\nu\bar{\nu}), \ldots$$

- Flavour part of $\mathcal{O}_i$:
  - new flavour structures, i.e. squark-mixing in SUSY
  or
  - minimal flavour violation
  * flavour symmetry / CP broken by Yukawa couplings only
  * $[b \to s] \leftrightarrow [b \to d] \leftrightarrow [s \to d]$
  * RG-invariant definition (d'Ambrosio et al.)

Theoretically clean flavour violating rare decays are very sensitive to possible new degrees of freedom:



$\leftrightarrow$ elektroweak precision data (10% $\leftrightarrow$ 0.1%)



$\sigma(V_{ij}) = 1\%$ $\mathcal{B}(B \to X_s \gamma)$

(courtesy of Gino Isidori)

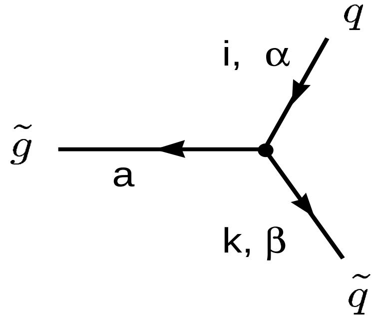
This indirect information is analogous to some direct information a linear collider could provide.

Correlations between B and Collider physics via squark mixing within SUSY

- In the unconstrained MSSM there are (too many ?) new contributions to flavour violation
  - CKM induced contributions from H^+, χ^+ exchanges
  - flavour mixing in the sfermion mass matrix

- Gluino-quark-squark coupling

  $-i g_s T^a_{\beta\alpha} (\Gamma^{ki}_{QL} P_L - \Gamma^{ki}_{QR} P_R)$



- Super KM basis $\tilde{q}_{L,Rj}$ $(j = 1, 2, 3)$
  - quark mass matrices are diagonal !
  - squarks are rotated 'parallel' to their fermionic superpartners !
  - in general not mass eigenstates: $\tilde{q}_{L,R} = \Gamma^{+}_{QL,R} \tilde{q}_i$

Sfermion mass matrix in uMSSM in $\tilde{q}_{L,R}$ basis:

$$\mathcal{M}^2_D = (F/D)^D_{6\times6} + \begin{pmatrix} m^2_{Q,LL} & m^2_{D,LR} \\ m^2_{D,RL} & m^2_{D,RR} \end{pmatrix}$$

$$\mathcal{M}^2_U = (F/D)^U_{6\times6} + \begin{pmatrix} m^2_{Q,LL} & m^2_{U,LR} \\ m^2_{U,RL} & m^2_{U,RR} \end{pmatrix}$$

from F, D terms	from soft breaking
3×3 diagonal submatrices	m^2_i not diagonal

all neutral gaugino couplings are flavour diagonal!

$\Rightarrow$ FCNC are induced by off-diagonal (off-generational) terms in $m^2_{LL}, m^2_{RR}, m^2_{LR}$

- General: $s \to d$ and $b \to d$ sector strongly constrained by data (kaon physics), but $b \to s$ not (yet?).

- New analysis of $b \to s$ sector Besmer, Greub, Hurth:

  Interference effects weaken the bounds significantly:

  $\Rightarrow$ new constraints of order 10^{-1} only.

- Consider correlations of flavour and collider physics Hurth, Porod

  Squarks can have large flavourviolating decay modes (compatible with present data from flavour physics).

More details (Nucl.Phys.D609,095001 (2001)):

Analysis based on a complete LL QCD calculation within the unconstraint MSSM :

- We use the mass-eigenstate formalism

  $\Leftrightarrow$ One-mass insertion approximation

$$\delta_{LR,23} = m^2_{LR,23}/\tilde{m}^2$$

  Sfermion propagator can be expanded as a series in terms of δ, where $\tilde{m}^2$ is an average mass.

- Derive bounds switching on one specific off-diagonal element only
  - $\delta_{LR,23}$ $(\delta_{LR,32})$ • $\delta_{LL,23}$

Systematic analysis of interference effects :

- Include all new-physics contributions (chargino, neutralino, charged Higgs, gluino)

- Stability of these separate bounds explored if all off-diagonal elements varied simultaneously.

- Various parameter scenarios:
  - Higgs bound $\leftrightarrow$ nontrivial stop mixing $X_t\, m_t = (m^2_{u,RL})_{33} - \mu m_t \cot\beta$
  - starting set: $\mu = 300\, GeV$, $M_{SUSY} = 500\, GeV$, $X_t = 750\, GeV$, $\tan\beta = 10$. $x = m^2_{\tilde{g}} / M^2_{susy} = 1$.
  - (A) $M_{susy} = 300\, GeV$, $X_t = 470\, GeV$
    (B) $M_{susy} = 500\, GeV$, $X_t = 750\, GeV$
    (C) $M_{susy} = 1000\, GeV$, $X_t = 1200\, GeV$.
  - $x = m^2_{\tilde{g}} / M^2_{susy} = 0.3\,,\, 0.5\,,\, 1\,,\, 2.$
  - $tan\beta = 2,\ 10,\ 30,\ 50$

$$L1 = \delta_{d,RL,23} + f(x)\delta_{d,RR,23} \times \delta_{d,RL,33} + f(x)\delta_{d,RL,22} \times \delta_{d,LL,23}$$

$$L2 = \delta_{d,LR,23} + f(x)\delta_{d,LR,22} \times \delta_{d,RR,23} + f(x)\delta_{d,LL,23,} \times \delta_{d,LR,33}$$

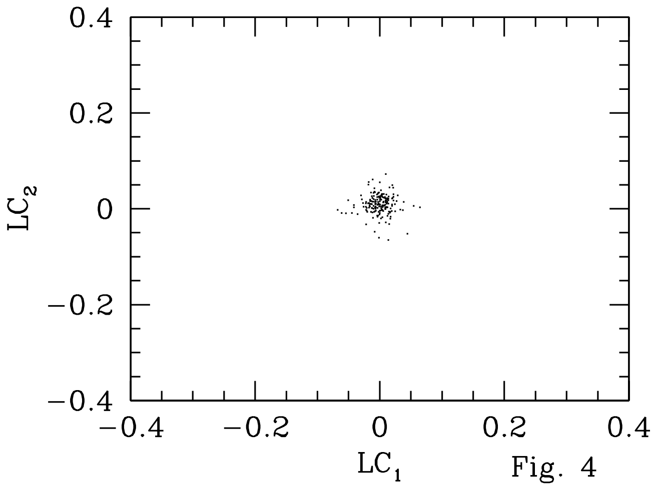


Fig. 4

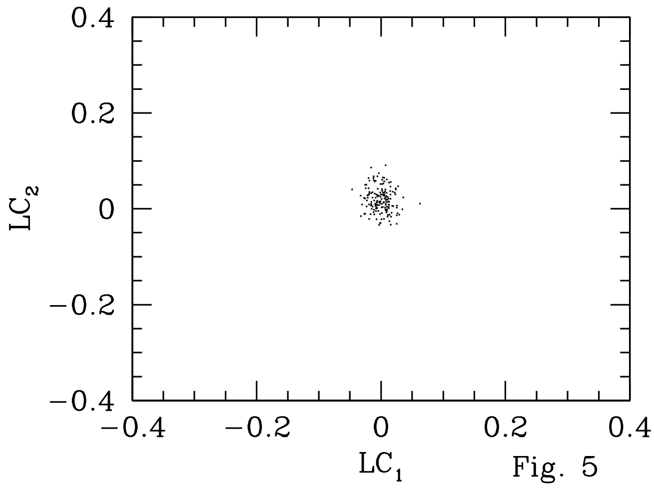


Fig. 5

Gluino- and SM contribution   all contributions

all δ_i varied

The combinations $LC1$ and $LC2$ stay stringently bounded over large parts of the supersymmetric parameter space, excluding the large $tan\beta$ and large μ regime (chargino contribution !).

Our new bounds are in general one order of magnitude weaker than the bound on the single off-diagonal element $\delta_{LR,23}$ derived by neglecting any kind of interference effects:

Compare with Masiero et al. '01 :
$\delta_{LR,23}$: 1.6×10^{-2} ($x = 1$ and $M_{\text{susy}} = 500\, GeV$)

Low energy constraints

- K-physics: ϵ'/ϵ, K^0-$\bar{K}^0$ mixing, ...
  $\Rightarrow$ neglect $1-2$ and $1-3$ mixing

- B-physics: $b \to s\gamma$, ΔM_{B_s}, ...
  most important beyond SM contributions: H^+, $\tilde{\chi}_i^+$, $\tilde{g}$

In practice:

- For simplicity: real parameters only

- QCD corrections for $b \to s\gamma$ as given in
  Borzumati et al., Phys. Rev. D62, 075005 (2000) and
  Besmer et al., Nucl.Phys.B609:359 (2001)

- ΔM_{B_s}, as given
  in Baek et al. , Phys. Rev. D64, 095001 (2001)

Correlations to Collider Physics

Hurth, Porod hep-ph/0311075

- Squark decays:

$$\begin{array}{rcl} \tilde{u}_i & \to & u_j \tilde{\chi}_k^0 \, , \, d_j \tilde{\chi}_l^+ \\ \tilde{d}_i & \to & d_j \tilde{\chi}_k^0 \, , \, u_j \tilde{\chi}_l^- \end{array}$$

  with $i = 1, .., 6$, $j = 1, 2, 3$, $k = 1, .., 4$ and $l = 1, 2$.

- These decays are governed by the same mixing matrices as the contributions to flavour violating low-energy B observables.

Strategy

- take SPS1a as starting point:

  $M_0 = 100$ GeV, $M_{1/2} = 250$ GeV
  $A_0 = -100$ GeV, $\tan\beta = 10$, $\mu > 0$
  $\Rightarrow$
  $M_2 = 192$ GeV, $\mu = 351$ GeV
  $m_{H^+} = 403$ GeV $m_{\tilde{g}} = 594$ GeV, $m_{\tilde{t}_1} = 400$ GeV
  $m_{\tilde{t}_2} = 590$ GeV, $m_{\tilde{q}_R} \simeq 550$ GeV, $m_{\tilde{q}_L} \simeq 570$ GeV

  (SPheno 2.0)

- vary off-diagonal squark mass entries.

- accept points with $2 \leq 10^4$ BR$(b \to s\gamma) \leq 4.5$ and $\Delta M_{B_s} \geq 14$ ps^{-1}

$\Rightarrow$ Typical results:

Branching ratios (in %) of u-type squarks

	$\tilde{\chi}_1^0 c$	$\tilde{\chi}_1^0 t$	$\tilde{\chi}_2^0 c$	$\tilde{\chi}_2^0 t$	$\tilde{\chi}_3^0 c$	$\tilde{\chi}_3^0 t$	$\tilde{\chi}_4^0 c$	$\tilde{\chi}_4^0 t$	$\tilde{\chi}_1^+ s$	$\tilde{\chi}_1^+ b$	$\tilde{\chi}_2^+ s$	$\tilde{\chi}_2^+ b$
$\tilde{u}_1$	4.7	18	5.2	9.6	6×10^{-3}	0	0.02	0	11.3	46.4	2×10^{-3}	4.7
$\tilde{u}_2$	.19.6	1.1	0.4	17.5	2×10^{-2}	0	6×10^{-2}	0	0.5	57.5	3×10^{-3}	2.9
$\tilde{u}_3$	7.3	3.7	20	1.4	6×10^{-2}	0	0.6	0	40.3	3.1	1	18.5
$\tilde{u}_6$	5.7	0.4	11.1	5.3	4×10^{-2}	5.7	0.6	13.2	22.9	13.1	0.6	8.0

Branching ratios (in %) of d-type squarks

	$\tilde{\chi}_1^0 s$	$\tilde{\chi}_1^0 b$	$\tilde{\chi}_2^0 s$	$\tilde{\chi}_2^0 b$	$\tilde{\chi}_3^0 s$	$\tilde{\chi}_3^0 b$	$\tilde{\chi}_4^0 s$	$\tilde{\chi}_4^0 b$	$\tilde{\chi}_1^- b$	$\tilde{\chi}_1^- t$	$\tilde{\chi}_2^- b$	$\tilde{\chi}_2^- t$	$\tilde{u}_1 W^-$
$\tilde{d}_1$	1.2	5.7	8.4	30.6	2×10^{-2}	1.5	0.2	0.9	16.6	34.1	0.6	0	0
$\tilde{d}_2$	.17.4	5.8	5.1	15.7	7×10^{-2}	7.4	0.3	09.2	9.7	19.7	0.7	0	8.8
$\tilde{d}_4$	14.7	21.7	11.3	2.2	5×10^{-2}	10.6	0.5	8.4	22.1	3.6	1.2	0	3.4
$\tilde{d}_6$	1.7	0.5	20.5	6.9	0.1	0.9	1.2	1.3	40.3	10.2	3.4	11.1	1.8

Gluino branching ratios larger than 1%.

Final state	BR [%]	Final state	BR [%]
$\tilde{u}_1 c$	12.9	$\tilde{d}_1 s$	7.2
$\tilde{u}_1 t$	5.7	$\tilde{d}_1 b$	19.8
$\tilde{u}_2 c$	0.4	$\tilde{d}_2 s$	6.1
$\tilde{u}_2 t$	7.6	$\tilde{d}_2 b$	4.7
$\tilde{u}_3 c$	0.6	$\tilde{d}_3 d$	10.0
$\tilde{u}_4 u$	5.5	$\tilde{d}_4 s$	3.5
$\tilde{u}_5 u$	3.0	$\tilde{d}_4 b$	4.9
		$\tilde{d}_5 d$	2.1

- $b \to s\gamma$ and ΔM_{B_s} (still ?) allow for large mixings between second and third generation squarks, for example $\tilde{t}_i$, $\tilde{c}_i$ can have large flavour violating decay modes,
- makes life at LHC potentially more interesting and more difficult,
- extra information from LC or flavour factories needed.