New physics scenarios: flavour benchmarks

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FlaviA net

- General considerations
- On the flavour-symmetry breaking scenarios
- MFV at large tanβ
  [*The SUSY case & Oliver's mastercode*]
- Beyond MFV
- Conclusions

General considerations

Two main strategies

Explicit NP scenario

[e.g.: mSUGRA, LH wih T-parity, ...]

Very predictive [correlations between low- & high-energy observables]

Not general [even within specific frameworks, such as low-energy SUSY]

Effective Field Theory approach

[new states above e.w. scale integrated out]

Not very predictive [even within low-energy observabels]

Very general [*the most general approach for low-energy observables*]

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EFT with specific flavour-symmetry assumptions

[e.g.: MFV, MFV+large tanβ, nMFV,...]

⬇

Predictive correlations of NP effects in low-energy observables

~~Generic EFT~~

flavour problem

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EFT with specific flavour-symmetry assumptions

[e.g.: MFV, MFV+large tanβ, nMFV,...]

→ key information about the underlying theory

↓

Predictive correlations of NP effects in low-energy observables

main tests from low-energy exp. data

▶ General considerations

high-energy exp. data

TeV-scale dynamics

[e.g.: SUSY, strong dynamics,..]

↓

pattern of NP effects in flavour-conserving high-energy observables

Explicit NP model

[or new EFT valid well above the e.w. scale]

↓

correlations of NP effects between low- & high-energy observables

main tests from low-energy exp. data

EFT with specific flavour-symmetry assumptions

[e.g.: MFV, MFV+large tanβ, nMFV,...]

↓

Predictive correlations of NP effects in low-energy observables

On the flavour symmetry-breaking scenarios

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i; Y) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\ d}(\phi_i, A_i, \psi_i)$$

► 3 identical fermion families ⇒ huge flavour-degeneracy: $U(3)^5$

► partial breaking of the flavour degeneracy:

$$\mathscr{L}_{\rm Yukawa} = \bar{Q}_L Y_D D_R \phi + \bar{Q}_L Y_U U_R \phi_c + \bar{L}_L Y_L e_R \phi + \text{h.c.}$$

$\bar{Q}_L$: $(\bar{3},1,1)$ D_R: $(1,1,3)$ Y_D: $(3,1,\bar{3})$

The SM Y's and any additional source of flavour symmetry breaking can be treated as spurions of

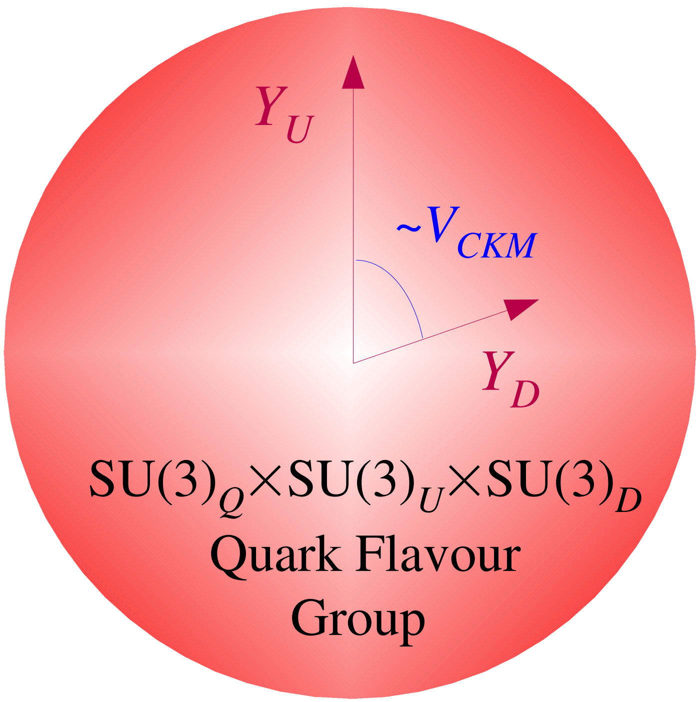
$$U(3)^5 = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R} \times \ldots$$

On the flavour symmetry-breaking scenarios

MFV: the Yukawa couplings are the only breaking sources of the flavour-symmetry group also beyond the SM [higher-dim. ops. constructed from SM and Y fields only respecting the $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$ invariance]

$(Y_U Y_U^{+})_{ij} \approx y_t^2 (V_{CKM})_{3i} (V_{CKM})_{3j}^{*}$ is the effective coupling ruling all the leading (measurable) FCNC amplitudes in the quark sector

- All FCNC amplitudes have the same GIM/CKM structure as in the SM ⇒ phase measurements –such as $A_{CP}(B \to \psi K_S)$– not sensitive to NP
- Only the flavour–independent magnitude of FCNCs can be modified by NP effects. Typical size: 10-30% deviations from SM in electroweak short-distance amplitudes assuming $\Lambda < 10$ TeV



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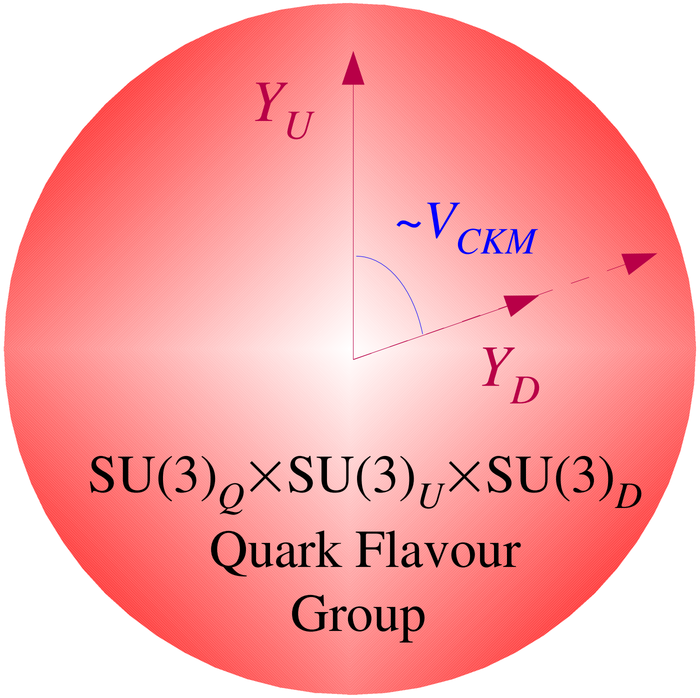
- Adding more Higgs doublets we can change the relative normalization of Y_U & Y_D (controlled by $\tan\beta$)
- Adding more *spurions* (new sources of flavour symmetry breaking) ⇒ next-to-MFV...



On the flavour symmetry-breaking scenarios

The absence of positive signal of new physics in the flavour sector [including the recent ΔM_{B_s} result] $\Rightarrow$ MFV very plausible scenario

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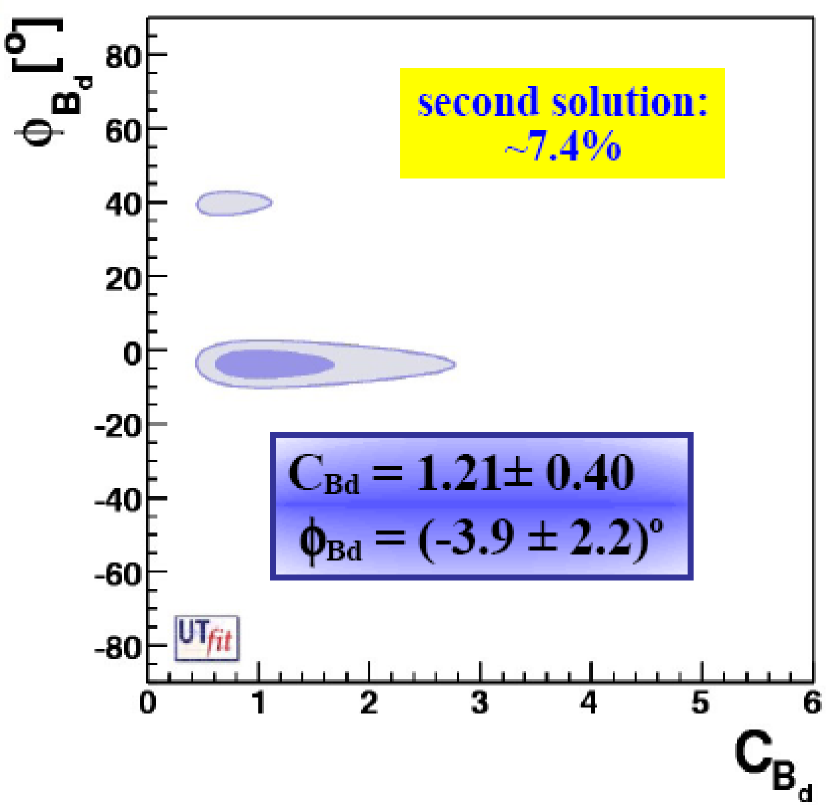
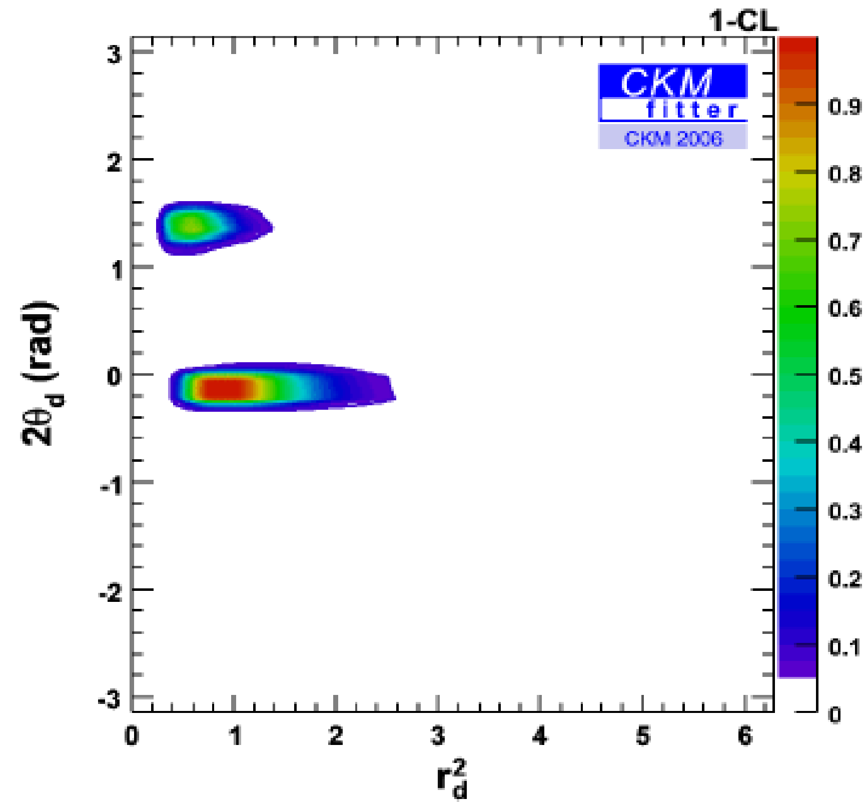
E.g.: CKM fits assuming NP in ΔF=2
+ negligible NP contributions
in *tree-level* observables

$$C_{B_q} e^{2i\phi_{B_q}} = r_q^2 e^{2i\theta_q} = \frac{\langle \bar{B}_q^0 | M_{12}^{SM+NP} | B_q^0 \rangle}{\langle \bar{B}_q^0 | M_{12}^{SM} | B_q^0 \rangle}$$





▶ *On the flavour symmetry-breaking scenarios*

The absence of positive signal of new physics in the flavour sector [including the recent ΔM_{B_s} result] $\Rightarrow$ MFV very plausible scenario

But the MFV hypothesis is still far from being clearly established

A reliable proof of the MFV hypothesis can only come from a positive evidence, which exhibit the [$b \to s$] - [$b \to d$] - [$s \to d$] link predicted by the symmetry

→ Key role of a few clean electroweak FCNC processes

[especially $B \to l^+l^-$, $B \to X_s\, l^+l^-$ & $K \to \pi\nu\nu$]

FLAVOUR COUPLING

ELECTROWEAK STRUCTURE

ELECTROWEAK STRUCTURE	$b \to s$ [$\sim \lambda^2$ in SM]	$b \to d$ [$\sim \lambda^3$ in SM]	$s \to d$ [$\sim \lambda^5$ in SM]
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$, ε_{Bs}	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$, ε_{Bd}	ε_K
$\Delta F=1$ 4-quark ops.	$A_{CP}(B_d \to \phi K)$	$A_{CP}(B_s \to \phi K)$	
gluon penguin	$A_{CP}(B_d \to \phi K)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ \gamma)$	$\Gamma(K_L \to \pi^0 l^+ l^-)$
γ penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s\ l^+ l^-)$ $A_{FB}(B \to X_s\ l^+ l^-)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ l^+ l^-)$ $A_{FB}(B \to \rho/\pi\ l^+ l^-)$	$\Gamma(K_L \to \pi^0 l^+ l^-)$
Z^0 penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s\ l^+ l^-)$ $A_{FB}(B \to X_s\ l^+ l^-)$ $\Gamma(B_s \to \mu\mu)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ l^+ l^-)$ $A_{FB}(B \to \rho/\pi\ l^+ l^-)$ $\Gamma(B_d \to \mu\mu)$	$\Gamma(K^+ \to \pi^+ \nu\nu)$ $\Gamma(K_L \to \pi^0 \nu\nu)$ $\Gamma(K_L \to \pi^0 l^+ l^-)$
H^0 penguin	$\Gamma(B_s \to \mu\mu)$	$\Gamma(B_d \to \mu\mu)$	

On the flavour symmetry-breaking scenarios

Some interesting recent developments/variations on the MFV theme:

- MFV in the quark sector can be realised within specific GUT frameworks
  - Key condition: small neutrino Yukawa couplings ($M_R < 10^{12}$ GeV)
  - Deviations from MFV in several GUT frameworks more likely in rare K decays rather than in B decays (for low $\tan\beta$)

Cirigliano, Grinstein, G.I. & Wise '06

- Classification of motivated non-MFV spurions still compatible with present data

Feldmann & Mannel '06

- The constrained-MFV [MFV + assumption no other operators beyond the SM ones] does not represent a consistent low-energy limit of the MSSM
  - CKM-type off-diagonal entries in squark mass matrices play an important role, even for small $\tan\beta$

Altmannshofer, Buras, Guadagnoli '07

Minimal Flavour Violation at large tanβ

$$\mathscr{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + L_L Y_L E_R H_D + \text{h.c.}$$

The Y are still the only irreducible spurions of $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

$$Y_D = \text{diag}(y_d, y_s, y_b) \qquad Y_U = (V_{ckm})^+ \times \text{diag}(y_u, y_c, y_t)$$

However, we are free to change the overall normalization of the Y :

$$y_u = m_u / \langle H_U \rangle \qquad y_d = m_d / \langle H_D \rangle = \tan\beta \; m_d / \langle H_U \rangle$$

For $\tan\beta = O(m_t / m_b) \gg 1$ we can have both y_t & y_b of order 1

[scenario particularly welcome in SO(10) GUT frameworks]

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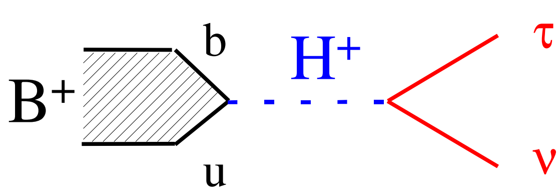
negligible non-standard effects in the standard CKM fits

However, we are free to change the overall normalization of the Y :

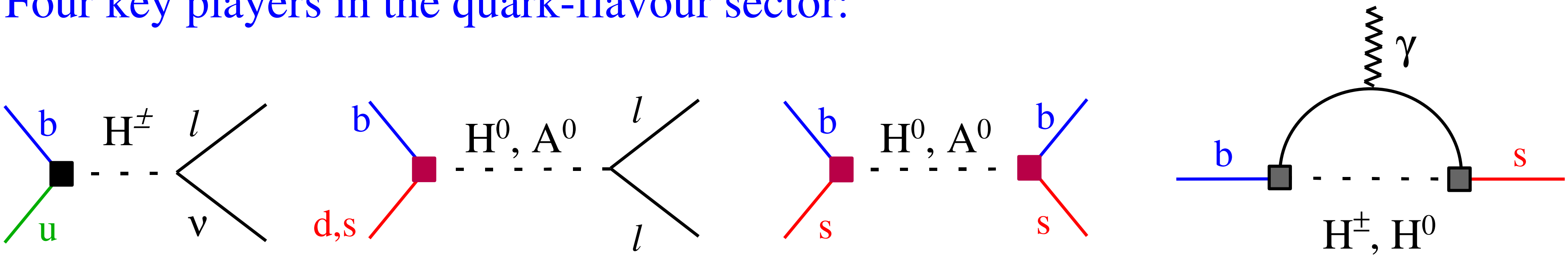
If $\tan\beta \gg 1$, visible non-standard effects in helicity-suppressed processes, e.g.:



$$B_{2HDM} = B_{SM} \times [\, 1 - (\tan\beta \; m_B/M_H)^2]^2$$

*Minimal Flavour Violation at large tan*β

Four key players in the quark-flavour sector:



$B^{\pm} \to l^{\pm}\nu$ $\quad$ $B_{s,d} \to l^{+}l^{-}$ $\quad$ ΔM_{B_s} $\quad$ $B \to X_s \gamma$

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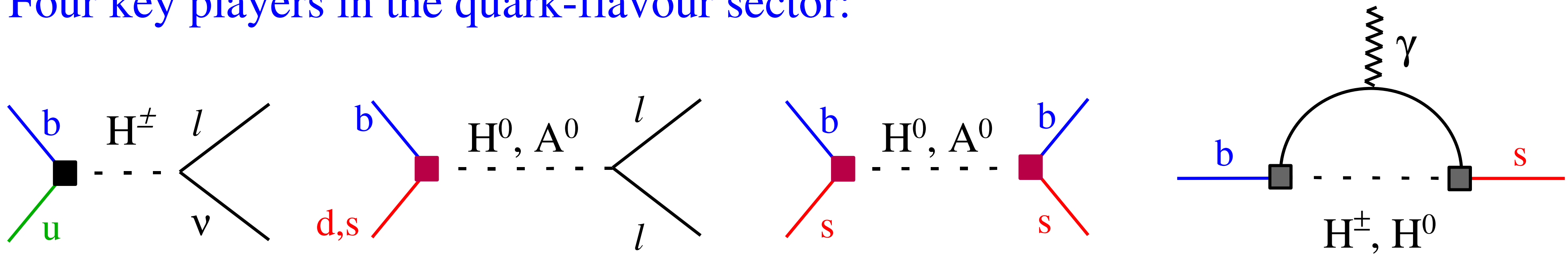

$B^\pm \to l^\pm \nu$	$B_{s,d} \to l^+ l^-$	ΔM_{B_s}	$B \to X_s \gamma$
~(10-50)% suppression	up to 100 × enhancement	~(0-20)% suppression	~(0-50)% enhancement

[qualitative general features for $M_H \sim 500$ GeV & tanβ ~ 50]

Despite several new free parameters, the framework exhibits a well defined pattern of enhancements & suppressions (consistent with present data)

The recent experimental infos on $B(B^\pm \to \tau^\pm \nu)$ [Belle & Babar '06] & ΔM_{B_s} [CDF '06], & the theoretical improvement on $B(B \to X_s \gamma)$ [Misiak et al. '06] finally allows us to start exploring this scenario more deeply

$B(B^\pm \to \tau^\pm \nu)^{SM} = (1.59 \pm 0.40)\, 10^{-4}$

$B(B^\pm \to \tau^\pm \nu)^{exp} = (0.88^{+0.68+0.11}_{-0.67\,-0.11})10^{-4}$ [Babar]

$B(B^\pm \to \tau^\pm \nu)^{exp} = (1.79^{+0.56+0.39}_{-0.49\,-0.46})10^{-4}$ [Belle]

MFV large-tanβ expectations:

~(10-50)% suppression

$\Delta M_{Bs}{}^{SM} = 21.5 \pm 2.6$ ps^{-1} [UTfit – pre CDF measurement]

$\Delta M_{Bs}{}^{exp} = 17.77 \pm 0.10 \pm 0.07$ ps^{-1} [CDF]

~(0-20)% suppression

$B(B_s \to \mu\mu)^{exp} / B(B_s \to \mu\mu)^{SM} < 23$ (90% CL) [CDF]

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$B(B \to X_s\gamma)^{exp} / B(B \to X_s\gamma)^{SM} = 1.13 \pm 0.12$ [Misiak et al. '06]

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No significant deviations from SM, but the +/– pattern of the large tanβ scenario is certainly consistent with [even slightly favored by] present data

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N.B.: crucial dependence from Lattice inputs & Vub

$$|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$$
$$\hat{B}_{B_d} = 0.836 \pm 0.068$$
$$f_B = 0.216 \pm 0.022\ \text{GeV}$$

[best values quoted before the recent measurements]

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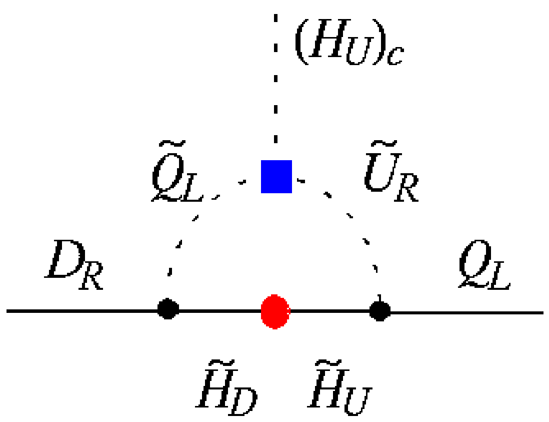
The game becomes particularly interesting in the explicit realization of this scenario within the MSSM ⇒ connection with flavour-conserving observables



key parameters:

$M_H \oplus \tan\beta \oplus [A_U, \mu, \tilde{m}_q]$

$(m_{h0})_{min} = f(A_U, \tan\beta, \tilde{m}_q)$

$(g-2)_\mu = f(\mu, \tan\beta, \tilde{m}_l)$

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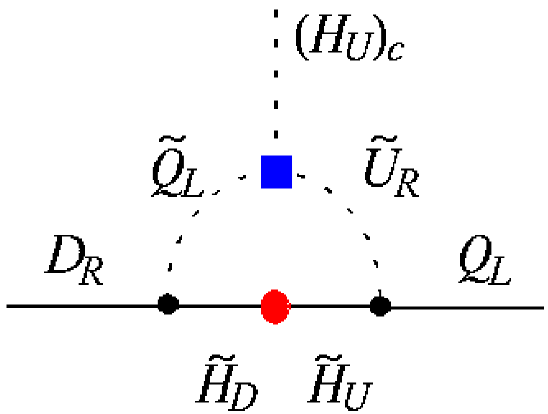

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$$(m_{h0})_{min} = f(A_U, \tan\beta, \tilde{m}_q)$$

$$(g-2)_\mu = f(\mu, \tan\beta, \tilde{m}_l)$$

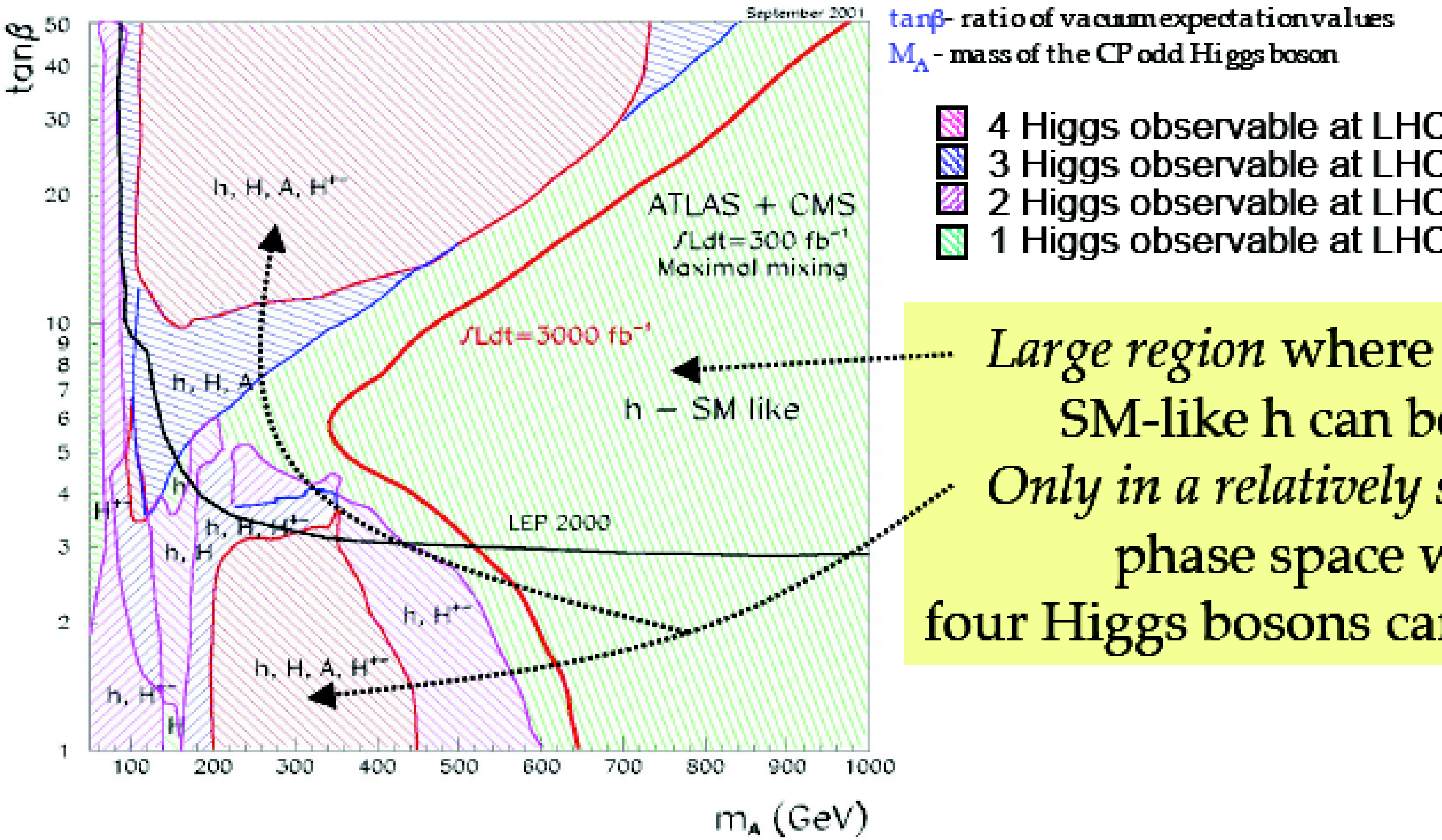
- Natural explanation of the present 3σ discrepancy from the SM in $(g-2)_\mu$
- Natural explanation of why $(m_{h0})_{min} > 115$ GeV

Recent phenomenological studies, including connections with LFV & Dark Matter

G.I. Paradisi, '06
Lunghi, Porod, Vives, '06
G.I., Mescia, Paradisi, Temes, '07

Natural benchmark for a deeper study of the connections between flavour physics and high-energy observables

MSSM Higgs Sector: LHC Discovery Reach



courtesy of
Oliver Buchmuller

Large region where only the light SM-like h can be detected.
Only in a relatively small region of phase space where all four Higgs bosons can be discovered.

Adding information from discoverable sparticles will help in the interpretation of the undetectable heavy Higgs sector. Yet, an unambiguous MSSM parameter extraction over the entire phase space cannot be guaranteed.

Also the potential upgrade to SuperLHC (~3000 fb^{-1}) does not change this conclusion (red line in plot). Though it would help to reduce the undetectable phase space.

Low-energy (LE) and Electroweak (EW) Constraints

Work started at the LHC Flavour workshop (collaboration from Experimentalist & Theorist)

S.Heinemeyer, G.I., P.Paradisi [TH],
O. Buchmuller, R. Cavanaugh,... [EXP]
work documented in the Yellow Report

A first start: Combine LE and EW calculations in one common code.
New Physics Parameter Space: MSSM

"Master Layer"
steers communication between the individual calculations / codes

"FeynHiggs"
http://www.feynhiggs.de/
calculation of the masses and mixing angles of the Higgs sector of the (real or complex) MSSM
&
EW observables in MSSM

"Flavour Observables"
Phys.Lett.B639:499-507,2006
Isidori & Paradisi
Calculation of B physics observables
In MSSm (&MFV)

"other observables"
e.g. cosmology constraints
NOT yet included but on to-do-list

Example: MSSM Parameter Fit

$$\chi^2 = \sum_i^{N_{const.}} \frac{(Const._i - Pred._i(MSSM))^2}{\Delta Const.^2 + \Delta Pred.^2}$$

Const. = Experimental Constraint value

Pred.(MSSM) = Predicted value for a given MSSM parameter set

2009 reference (pessimistic) scenario:

Observable	Constraint	theo. error
$R_{\mathrm{BR}_{b\to s\gamma}}$	1.127 ± 0.1	0.1
$R_{\Delta M_s}$	0.8 ± 0.2	0.1
$\mathrm{BR}_{b\to\mu\mu}$	$(3.5 \pm 0.35) \times 10^{-8}$	2×10^{-9}
$R_{\mathrm{BR}_{b\to\tau\nu}}$	0.8 ± 0.2	0.1
Δa_μ	$(27.6 \pm 8.4) \times 10^{-10}$	2.0×10^{-10}
M_W^{SUSY}	80.392 ± 0.020 GeV	0.020 GeV
$\sin^2\theta_W^{\mathrm{SUSY}}$	0.23153 ± 0.00016	0.00016
M_h^{light} (SUSY)	> 114.4 GeV	3.0 GeV

MSSM Parameter in the Fit

- $\tan\beta$ - ratio of vacuum expectation values
- M_A - mass of the CP odd Higgs boson
- A - tri-linear Higgs-stop coupling, all tri-linear couplings are set equal
- μ - Higgs mixing parameter
- M_{squark} - squark soft SUSY-breaking parameter; $M_{squark}=2M_{slepton}$

Assumptions (varied to evaluate systematic):
M_2=200 GeV, M_3=300 GeV, $M_1=1/2M_2$
$M_{gluino}=M_{squark}$
$M_{1,2,3}$ - Soft Susy breaking parameters in the gaugino sector

S.Heinemeyer, G.I., P.Paradisi [TH],
O. Buchmuller, R. Cavanaugh,... [EXP]
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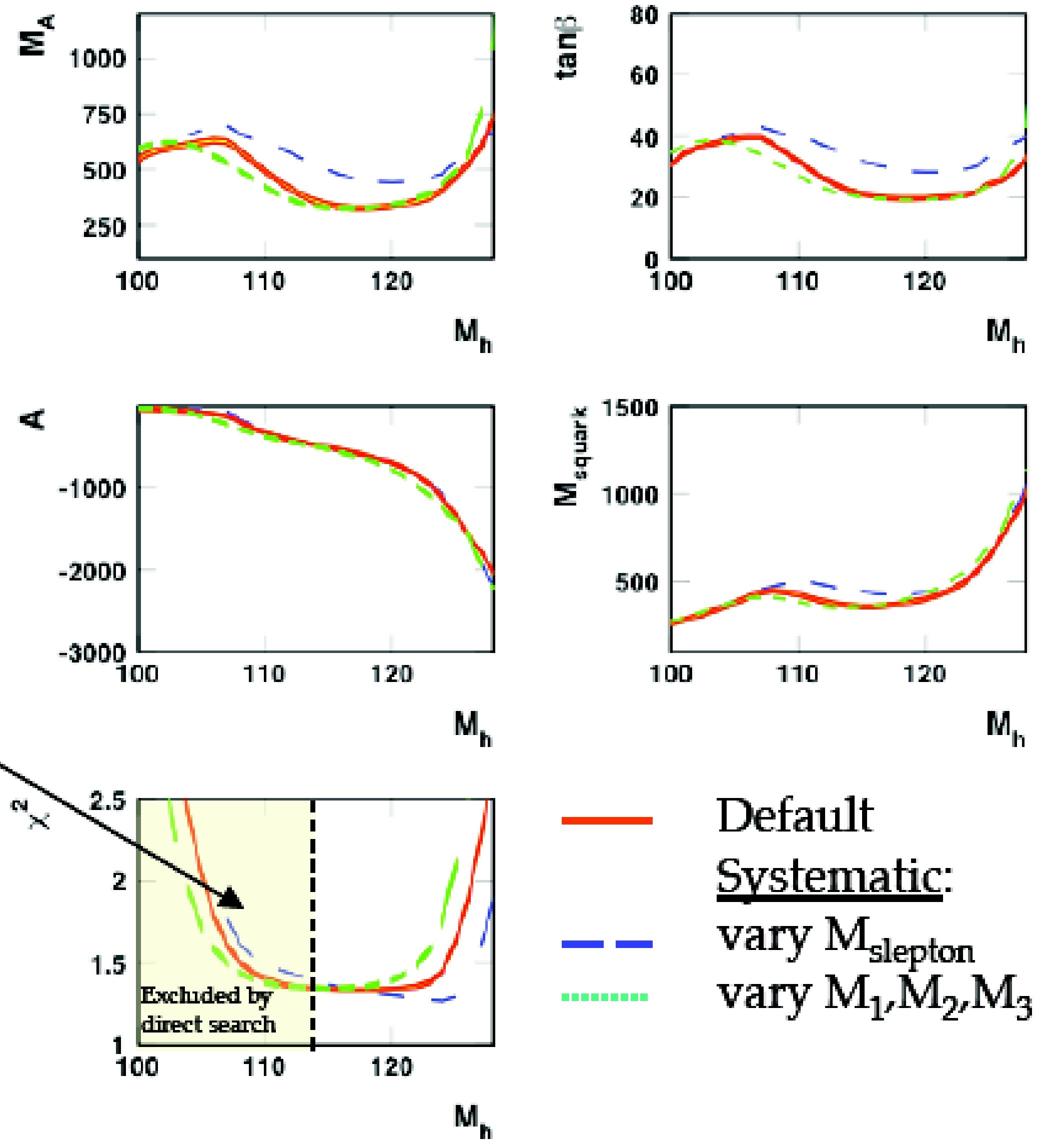
χ^2 Scan in the Mass of the Lightest Higgs h

Scan MSSM parameter space as function of M_h:

Determine for a given M_h the MSSM parameter set that minimizes the χ^2.

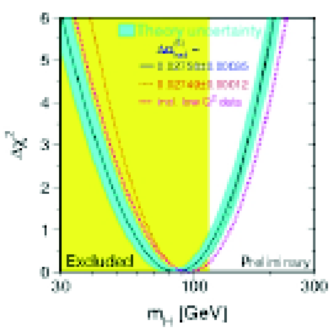
χ^2 minimum of the scan is between M_h~110 GeV and M_h~125 GeV.

2009 scenario



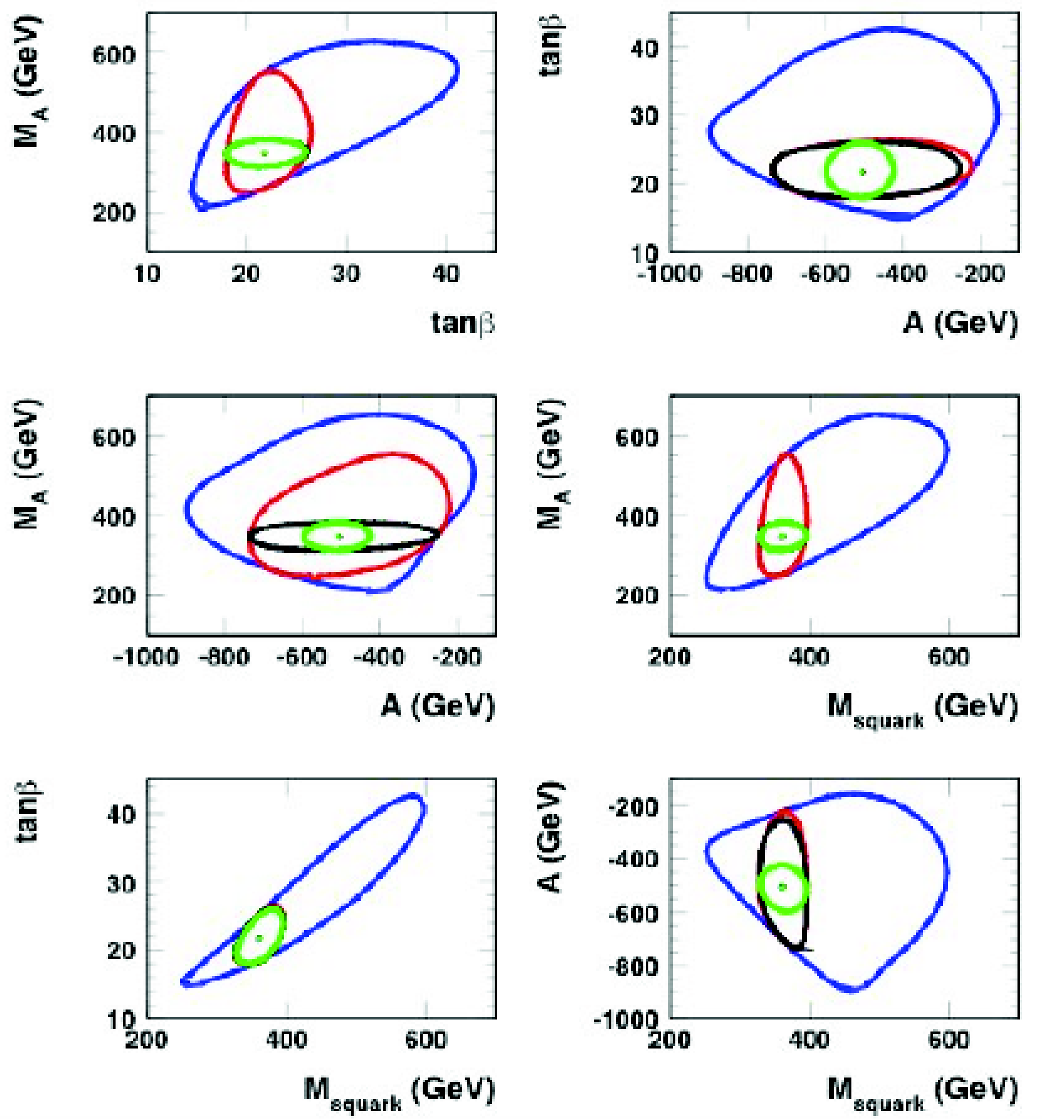
Documented in LHC Flavour Workshop - Yellow Report

Comparison: SM Fit



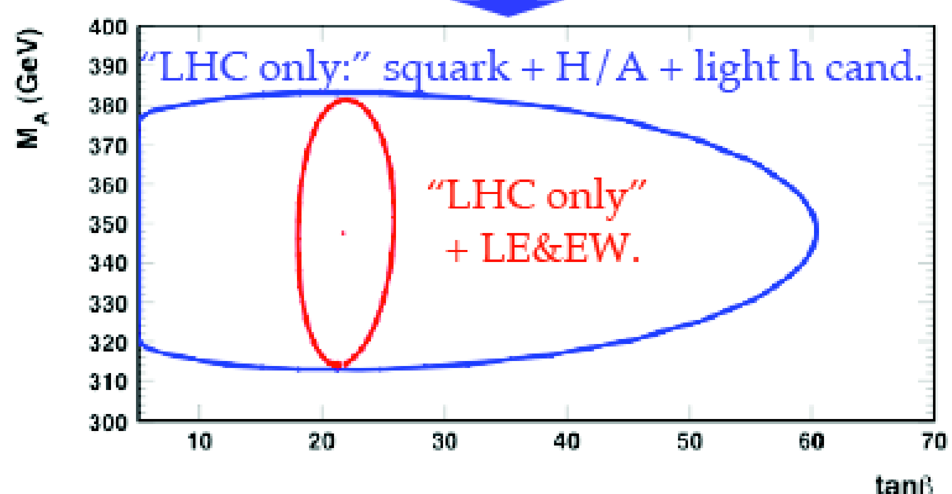
This nicely <u>illustrates</u> the potential of external constraints to restrict the allowed MSSM parameter space

Interpretation & Consistency



- LE&EW: low-energy (LE) and EW constraints
- LE&EW + squark candidate
- LE&EW + squark cand. + H/A cand.
- LE&EW + squark + H/A + light h cand.

Including LW&EW constraints facilitates the determination of fundamental MSSM parameters



Example: Almost no information on tanβ without external constraints. Note that a direct measurement of tanβ is very difficult at the LHC

Illustrative Example

Beyond MFV

Is there still room for models with sizable non-minimal flavour-breaking structures ?

No - if we want to have non-standard particles carrying flavour quantum numbers at the TeV scale

▶ *Beyond MFV*

Is there still room for models with sizable non-minimal flavour-breaking structures ?

No - if we want to have non-standard particles carrying flavour quantum numbers at the TeV scale

→ super-heavy flavored particles [split-SUSY]

→ minimal deviations from MFV [several examples within GUTs]

→ deviations from MFV only in specific electroweak or flavour structures [e.g.: Little Higgs with T-parity, non-MFV A_U in MSSM]

Several contributions in the recent literature, documented in the Yellow Report

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Ciuchini et al. '07
Cirigliano et al. '06

Buras et al. '06- '07

connections with low-energy LFV observables [$\mu \to e\gamma$, ...]

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Worth to analyse specific benchmarks in these cases ?

- Interesting to investigate NP sensitivity & correlations of low-energy observables
- Less interesting to study low/high-energy correlations (at least at present...)

Conclusions

At present, the most useful flavour benchmarks are well-defined flavour-symmetry breaking patterns which can be defined independently from high-energy physics

MFV with one Higgs doublet and MFV at large tanβ are two well-motivated examples of such patterns:

- consistent EFT formulations which allow us to establish correlations among different flavour-physics observables
- natural implementation within low-energy SUSY ⇒ correlations between low- and high-energy data ⇒ interesting tool-development started within this wkshp

Difficult to establish clear connections between low- and high-energy physics without a guiding flavour-symmetry principle...

- worth to explore the NP sensitivity of all accessible low-energy observables
- less interesting to perform dedicated studies of low ↔ high energy correlations in scenarios with too many free parameters