Flavour in the Era of the LHC

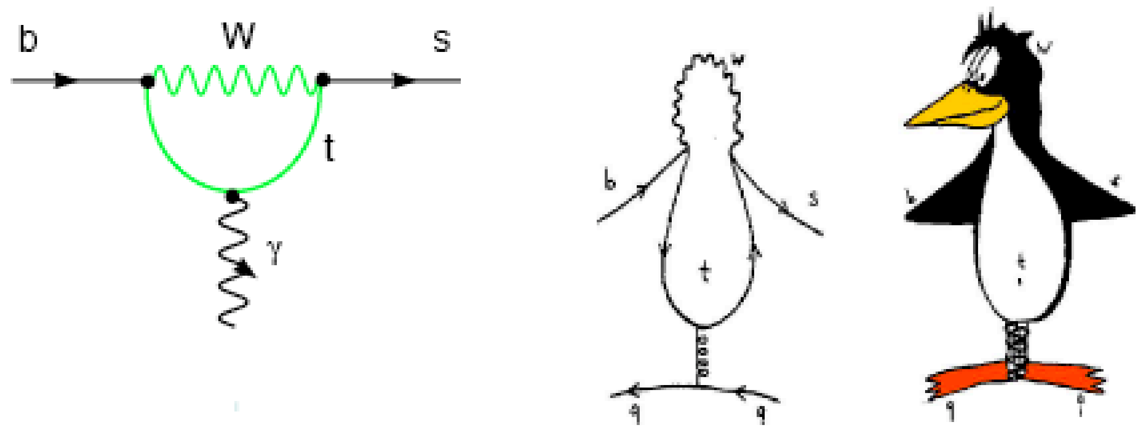
Brief Report from the CERN Flavour Workshop

Tobias Hurth (CERN, SLAC)

5th SuperB Workshop, Paris, 11th of May 2007

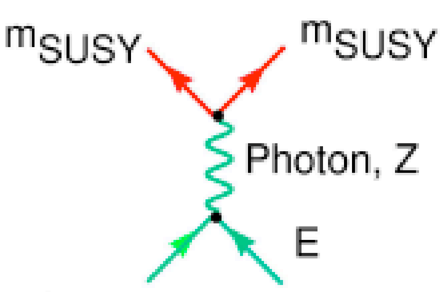
Indirect exploration of higher scales via flavour observables

- Flavour changing neutral current processes like $b \to s\gamma$ or $b \to s\ell^+\ell^-$ directly probe the SM at the one-loop level.

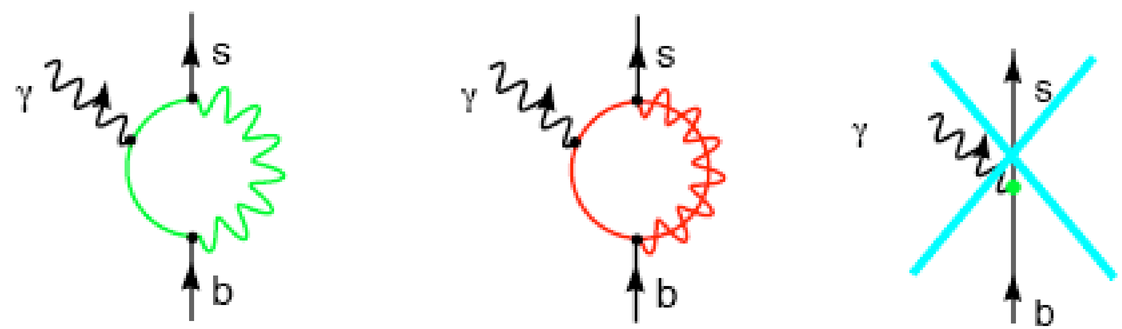


- Indirect search strategy for new degrees of freedom beyond the SM

Direct:



Indirect:



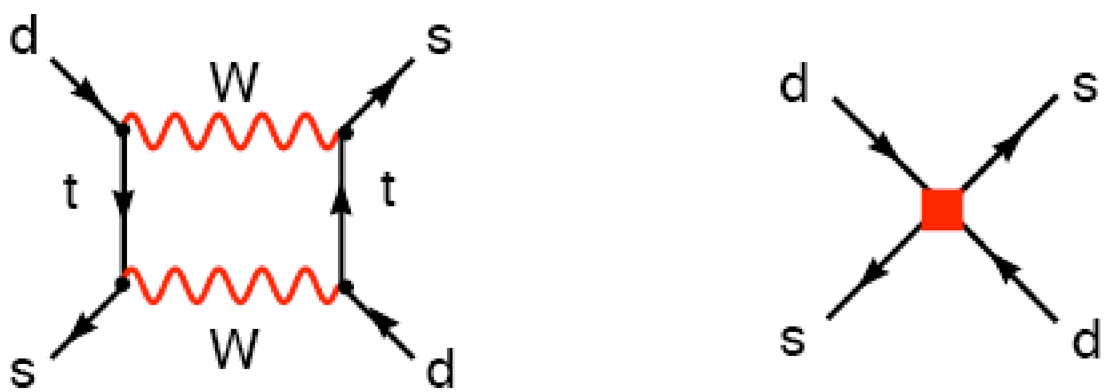
- High sensitivity for 'New Physics' ($\leftrightarrow$ electroweak precision data, 10% $\leftrightarrow$ 0.1%)

- Immense potential for synergy and complementarity between collider and flavour physics within the search for new physics

Flavour problem or how do FCNCs hide?

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

- SM as effective theory valid up to cut-off scale Λ_{NP}
- $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$: $c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda^2 \times (\bar{s}\, d)^2 \Rightarrow \Lambda_{\mathrm{NP}} > 100\,\mathrm{TeV}$



- Natural stabilisation of Higgs boson mass (hierarchy problem) $\Rightarrow \Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$
  (i.e. supersymmetry, little Higgs, extra dimensions)
- In addition: EW precision data $\leftrightarrow$ little hierarchy problem $\Rightarrow \Lambda_{\mathrm{NP}} \sim 3 - 10\mathrm{TeV}$

Possible New Physics at the TeV scale has to have a very non-generic flavour structure

This fundamental flavour problem has to be solved by any new physics scenario.

Rare decays and CP violating observables exclusively allow to analyse it.

Example: Supersymmetry

- In the MSSM too many contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix (disalignment)

$\Rightarrow$ Supersymmetric flavour problem

- In the MSSM too many (44) phases: stringent bounds on phases by flavour-diagonal CP violating observables (EDM)

$\Rightarrow$ Supersymmetric CP problem

- $b \to s\gamma$ is sensitive to the mechanism of SUSY breaking, because in the limit of exact supersymmetry:

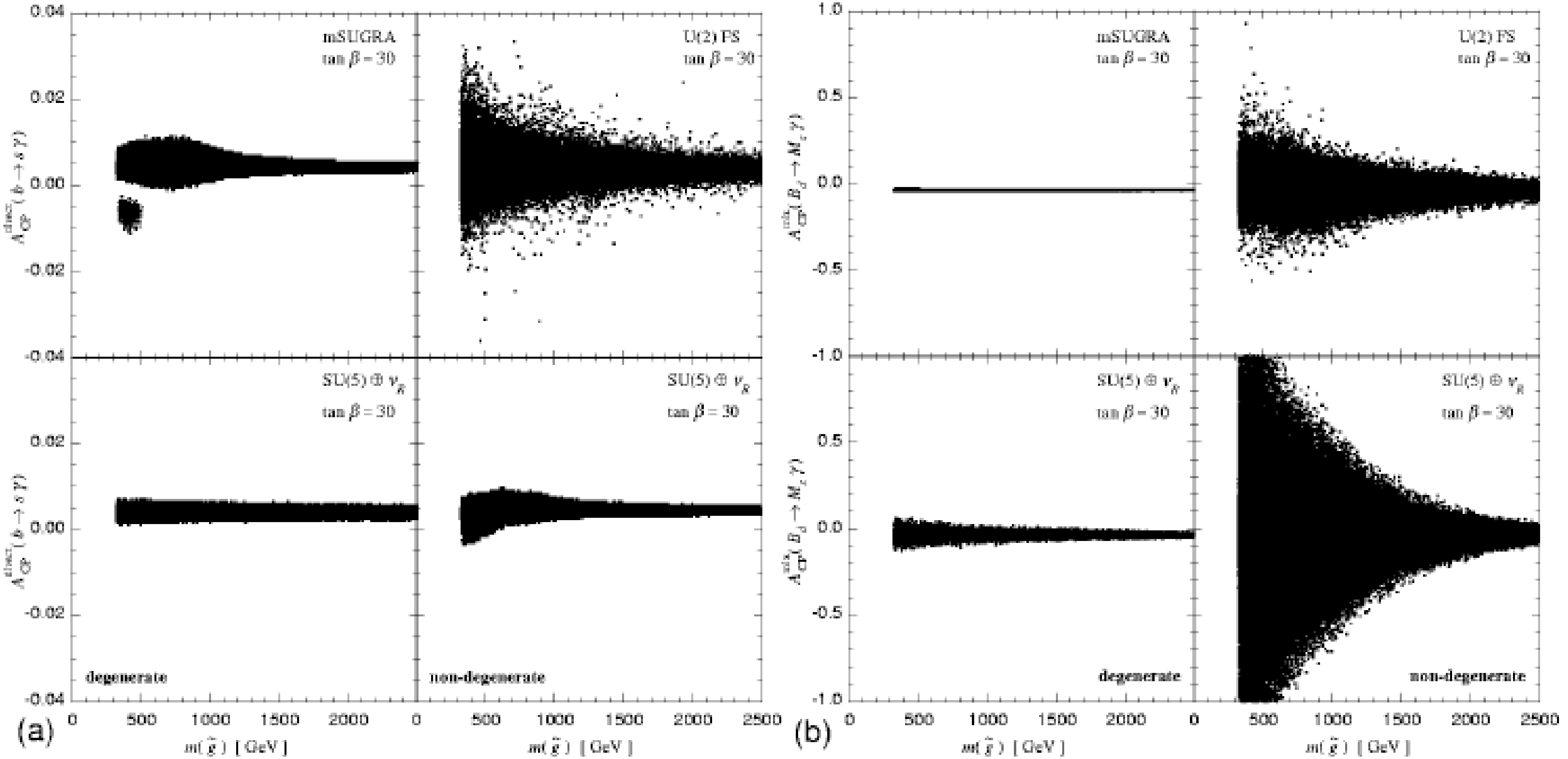
$$BR(b \to s\gamma) = 0\,!$$

Dynamics of flavour $\leftrightarrow$ Mechanism of SUSY breaking

$\Rightarrow$ Discrimination between various SUSY-breaking mechanism

Discrimination between various SUSY-breaking mechanism via flavour observables

Goto et al



Direct CP asymmtry in $b \to s\gamma$ Mixing-induced CP asymmtry $B_d \to M_s\gamma$

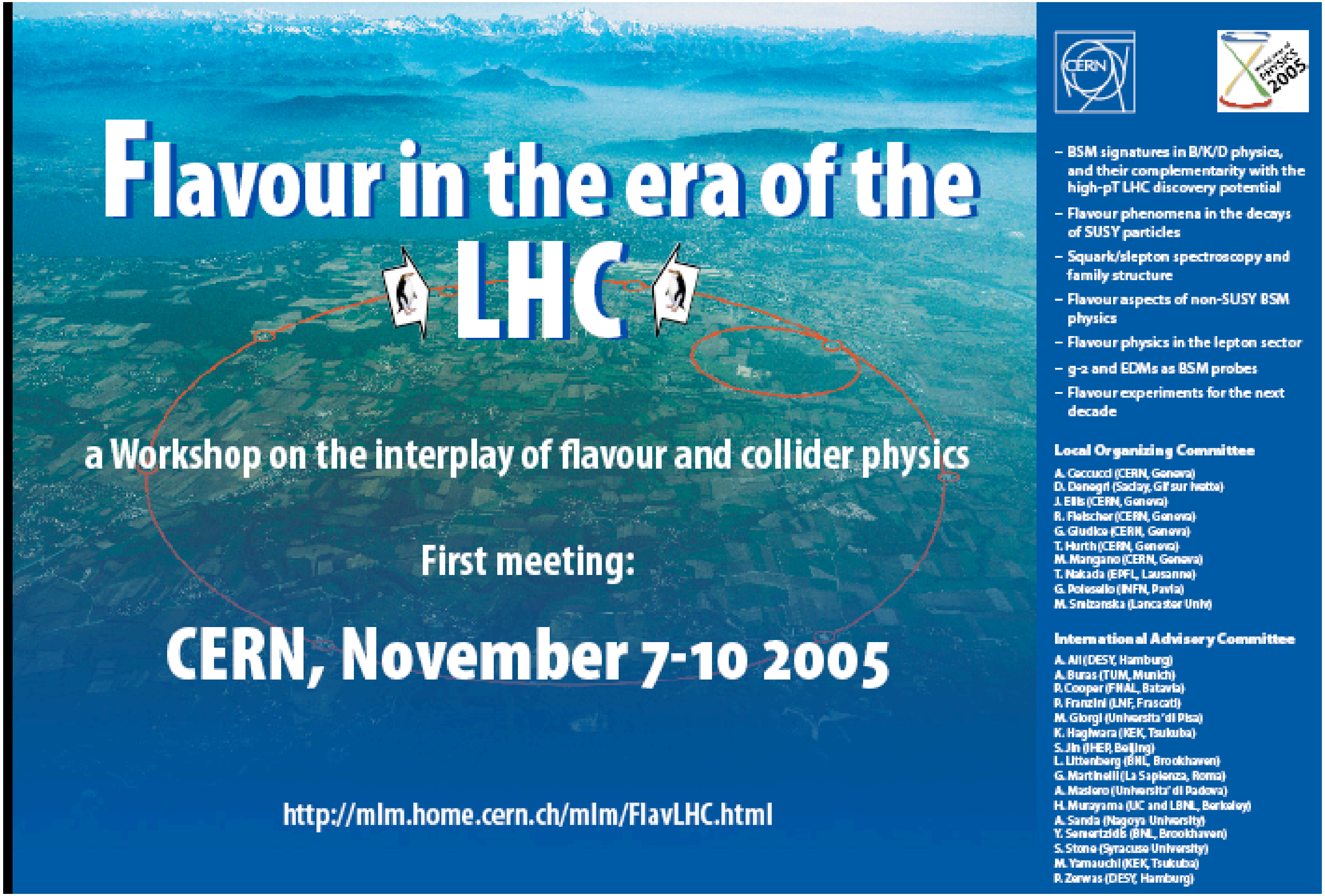
as functions of the gluino mass

Sensitivities (Super-B): $\Delta = \pm 0.004$ $\Delta = \pm 0.02$ (theoretically limited)

The indirect information will be most valuable when the general nature of new physics will be identified in the direct search (LHC), specifically when the mass scale of the new physics will be fixed.

⇒ CERN workshop on the interplay of flavour and collider physics

Fleischer, Hurth, Mangano see http://mlm.home.cern.ch/mlm/FlavLHC.html



5 meetings between 11/2005 and 3/2007, Yellow Report to appear

FLAVOUR in the era of the LHC

a workshop on the interplay of flavour and collider physics

1. opening plenary meeting: CERN, November 7-11 2005
2. working group meeting: CERN, February 6-8 2006
3. working group meeting: CERN, May 15-17 2006
4. working group meeting: CERN, October 9-11 2006
5. final plenary meeting: CERN, March 26-29 2007

see http://mlm.home.cern.ch/mlm/FlavLHC.html

Goals of the workshop

- to outline and document a programme for flavour physics for the next decade,
- to discuss new experimental proposals in flavour physics,
- to address the complementarity and synergy between the LHC and the flavour factories in our search for new physics.

Working group reports being finalized, expected delivery June 2007

- BSM signatures in B/K/D physics, and their complementarity with the high-pT LHC discovery potential
- Flavour phenomena in the decays of SUSY particles
- Squark/slepton spectroscopy and family structure
- Flavour aspects of non-SUSY BSM physics
- Flavour physics in the lepton sector
- g-2 and EDMs as BSM probes
- Flavour experiments for the next decade

Official list of research topics:

Incomplete list of experimental proposals:

- Super-LHCb (CERN)
- Super B flavour factories at KEK and at Frascati
- $K^+ \to \pi^+ \nu\nu$ NA48/3 (CERN); $K_L^0 \to \pi^0 \nu\nu$ E14 (J-PARC)
- $\mu \to e\gamma$, MEG (PSI); μe conversion, Mu2e (FNAL)
- rare tau decays at CMS (CERN) and at Super B flavour factories
- universality tests in π decays, PEN (PSI) and PIENU (TRIUMF), and in kaon decays, NA48 (CERN)
- neutron EDM experiments at SNS, PSI, and ILL Grenoble, muon EDM at PSI, deuteron EDM at BNL, and electron EDM in Oklahoma and LBNL

Two spotlights

Possible correlation between squark decays and flavour observables

Minimal flavour violation in Susy with large $\tan\beta$

Model-independent analysis: New flavour structures in $b \to s$ transitions ?

Data from K and B_d physics show that new sources of flavour violation in $s \to d$ and $b \to d$ are strongly constrained, the possibility of large new contributions to $b \to s$ still remains open.

Hints from model building

Susy-GUTs relate the large mixing angle in the neutrino sector to large mixing in the right-handed b-s sector.

Moroi, Harnik et al.

Possible direct correlations between B and collider physics

- Squark decays:

$$\tilde{u}_i \to u_j \tilde{\chi}^0_k \, , \, d_j \tilde{\chi}^+_l \qquad \tilde{d}_i \to d_j \tilde{\chi}^0_k \, , \, u_j \tilde{\chi}^-_l$$

  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 observables.

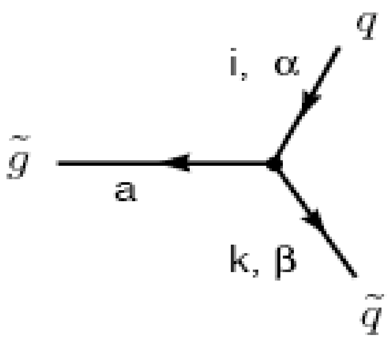
  Squarks can have large flavourviolating decay modes, compatible with present data from flavour physics. Hurth, Porod

- Flavour-tagging at LHC difficult:
  makes life at LHC potentially more interesting and more difficult, extra information from ILC or flavour factories needed.

Documented in the LHC Flavour Workshop - Yellow Report

More details on correlations via squark mixing:

- In the unconstrained MSSM (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: $-ig_s T^a_{\beta\alpha}(\Gamma^{ki}_{QL} P_L - \Gamma^{ki}_{QR} P_R)$



- Possible disalignment of quarks and squarks

Strategy

- take SPS1a' as starting point:

  $M_0 = 70$ GeV, $M_{1/2} = 250$ GeV
  $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$
  $\Rightarrow$
  $M_2 = 193$ GeV, $\mu = 403$ GeV
  $m_{H^+} = 439$ GeV $m_{\tilde{g}} = 608$ GeV

  (SPheno 2.0)

- use bounds from $BR(b \to s\gamma)$, $BR(b \to s\ell^+\ell)$, ΔM_s
- vary flavour-nondiagonal parameters
  (off-diagonal squark mass entries)

$\Rightarrow$ Typical results:

⇒ Typical results:

Branching ratios (in %) for squark and gluino decays

	$\tilde{\chi}_1^0 c$	$\tilde{\chi}_1^0 t$	$\tilde{\chi}_2^0 c$	$\tilde{\chi}_2^0 t$	$\tilde{\chi}_1^+ s$	$\tilde{\chi}_1^+ b$	$\tilde{\chi}_2^+ b$	$\tilde{u}_1 Z^0$	$\tilde{u}_1 h^0$
$\tilde{u}_1$	1.4	16.8				81.1			
$\tilde{u}_2$	9.1		21.0	3.6	42.9	14.3		5.3	1.3
$\tilde{u}_3$	20.9		21.9		47.5	1.1		1.9	5.5
$\tilde{u}_6$	1.5	2.7	1.6	3.7	4.0	14.1	14.2	39.2	5.2
	$\tilde{\chi}_1^0 s$	$\tilde{\chi}_1^0 b$	$\tilde{\chi}_2^0 s$	$\tilde{\chi}_2^0 b$	$\tilde{\chi}_3^0 b$	$\tilde{\chi}_4^0 b$	$\tilde{\chi}_1^- c$	$\tilde{\chi}_1^- t$	$\tilde{u}_1 W^-$
$\tilde{d}_1$	1.4	5.7	2.7	2.8			6.5	28.1	27.3
$\tilde{d}_2$	4.2	2.9	6.3	17.8			13.4	18.8	34.8
$\tilde{d}_4$	1.8		23	3.7			41.5	5.8	20.0
$\tilde{d}_6$	77.3	15.9	4.6	3.7	2.4	2.4	7.7	5.1	40.
	$\tilde{d}_1 s$	$\tilde{d}_1 b$	$\tilde{d}_2 s$	$\tilde{d}_2 b$	$\tilde{d}_3 d$	$\tilde{d}_4 s$	$\tilde{d}_5 d$	$\tilde{d}_6 s$	$\tilde{d}_6 b$
$\tilde{g}$	3.4	12.8	5.5	7.5	8.2	5.8	5.1	2.1	2.2
	$\tilde{u}_1 c$	$\tilde{u}_1 t$	$\tilde{u}_2 c$	$\tilde{u}_3 c$	$\tilde{u}_4 u$	$\tilde{u}_5 u$			
	1.2	14	8.8	7.9	8.2	5.5			

$\text{BR}(b \to s\gamma) = 3.8 \cdot 10^{-4}$, $|\Delta(M_{B_s})| = 19.6\ \text{ps}^{-1}$ and $\text{BR}(b \to s\mu^+\mu^-) = 1.59 \cdot 10^{-6}$.

resulting up-squark masses in GeV are 315, 488, 505, 506, 523 and 587

resulting down-squark masses are 457, 478, 505, 518, 529, 537

Minimal Flavour Violation hypothesis

All flavour- and CP-violating interactions be linked to the known Yukawa couplings

RG-invariant definition based on a symmetry principle:
(Yukawa couplings are introduced as background values of fields transforming under the flavour group $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$) d'Ambrosio et al.

MFV predictions to be tested:

- usual CKM relations between $[b \to s] \leftrightarrow [b \to d] \leftrightarrow [s \to d]$ transitions:
  -we need high-precision $b \to s$, but also $s \to d$ measurements
  -$\mathcal{B}(\bar{B} \to X_d\gamma) \leftrightarrow \mathcal{B}(\bar{B} \to X_s\gamma)$, $\mathcal{B}(\bar{B} \to X_s\nu\bar{\nu}) \leftrightarrow \mathcal{B}(K \to \pi^+\nu\bar{\nu})$

- CKM phase only source of CP violation:
  -phase measurements in $B \to \phi K_s$ or $\Delta M_{B_{(s/d)}}$ are not sensitive to new physics
  -RG-invariant extension allowing for flavour-blind phases Hurth,Lunghi,Porod

Real MFV bounds are important: measurements beyond those unambiguously indicate new flavour structures.

Simplified (so-called constraint) version of MFV: 'the relevant operators in effective Hamiltonians for weak decays are the same as in the SM.'
This scenario does not represent a consistent low-energy limit of the MSSM
Yukawa-type off-diagonal entries in squark mass matrix are important
see Altmannshofer et al.,hep-ph/0703200

The MFV hypothesis is far from being verified.

Search for large $\tan\beta$ within MFV in SUSY Isidori, Paradisi, hep-ph/0605012

MFV large-tanβ expectations:

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

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

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

~(10-50)% suppression

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

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

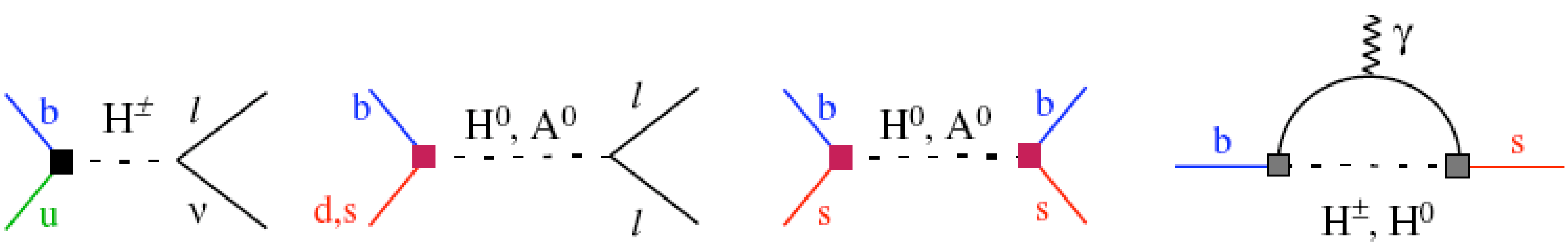
~(0-20)% suppression

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

up to 100 × enhancement

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

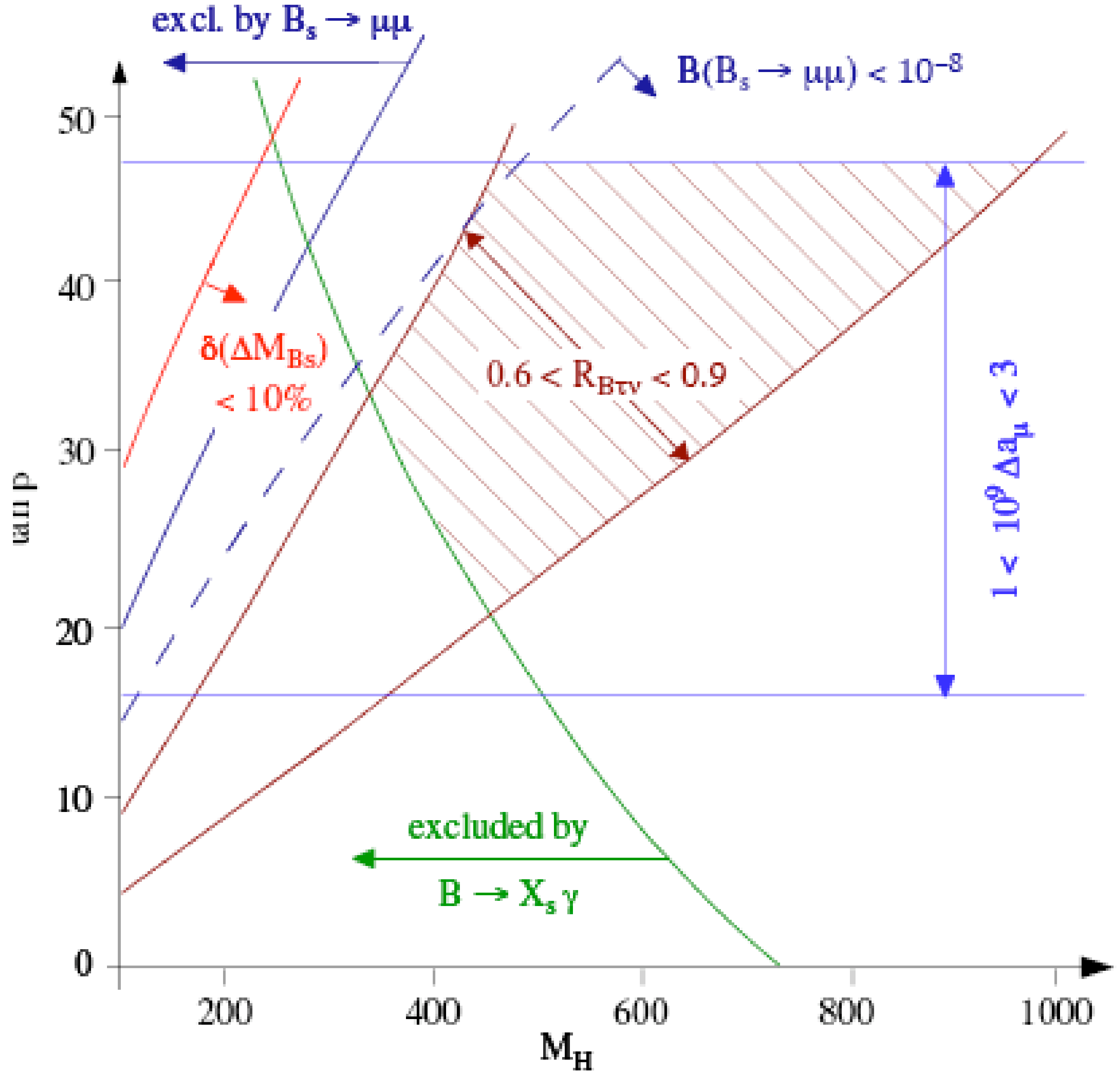
~(0-50)% enhancement



Courtesy of Gino Isidori

Search for large $\tan\beta$ within MFV in SUSY Isidori, Paradisi,hep-ph/0605012

B-physics observables and $(g-2)_\mu$ in the $M_{H^\pm}$–$\tan\beta$ plane:



Crosscheck of benchmark points

with all B-physics bounds,

all SUSY collider searches,

Higgs sector constraints,

EW precision data

$M_{\tilde{q}} = 1, M_{\tilde{l}} = 0.5, M_2 = 0.3, M_1 = 0.2, \mu = 0.5, A_U = -1.0$ TeV $\quad R_{B\tau\nu} := \frac{BR^{\mathrm{SUSY}}(B_u \to \tau\nu)}{BR^{\mathrm{SM}}(B_u \to \tau\nu)}$

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

Courtesy of Oliver Buchmüller

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

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

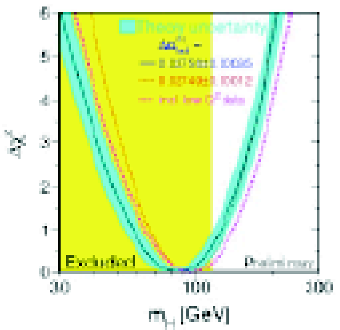
S.Heinemeyer, G.I., P.Paradisi [TH],
O. Buchmuller, R. Cavanaugh,... [EXP]
work documented in the Yellow Report

Scan MSSM parameter space as function of M_h:

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

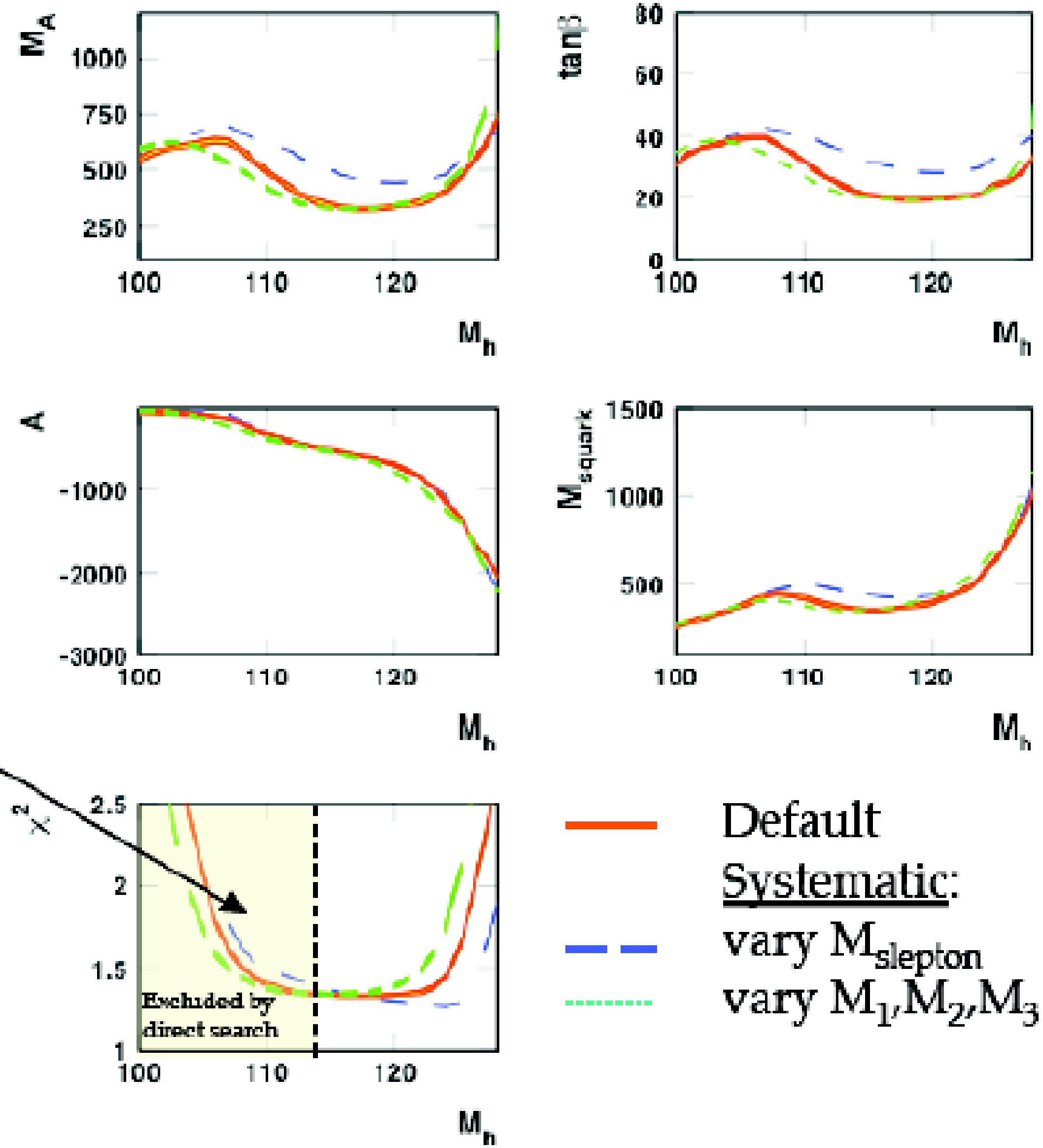
χ^2 minimum of the scan is between M_h~110 GeV and M_h~125 GeV.

Comparison: SM Fit

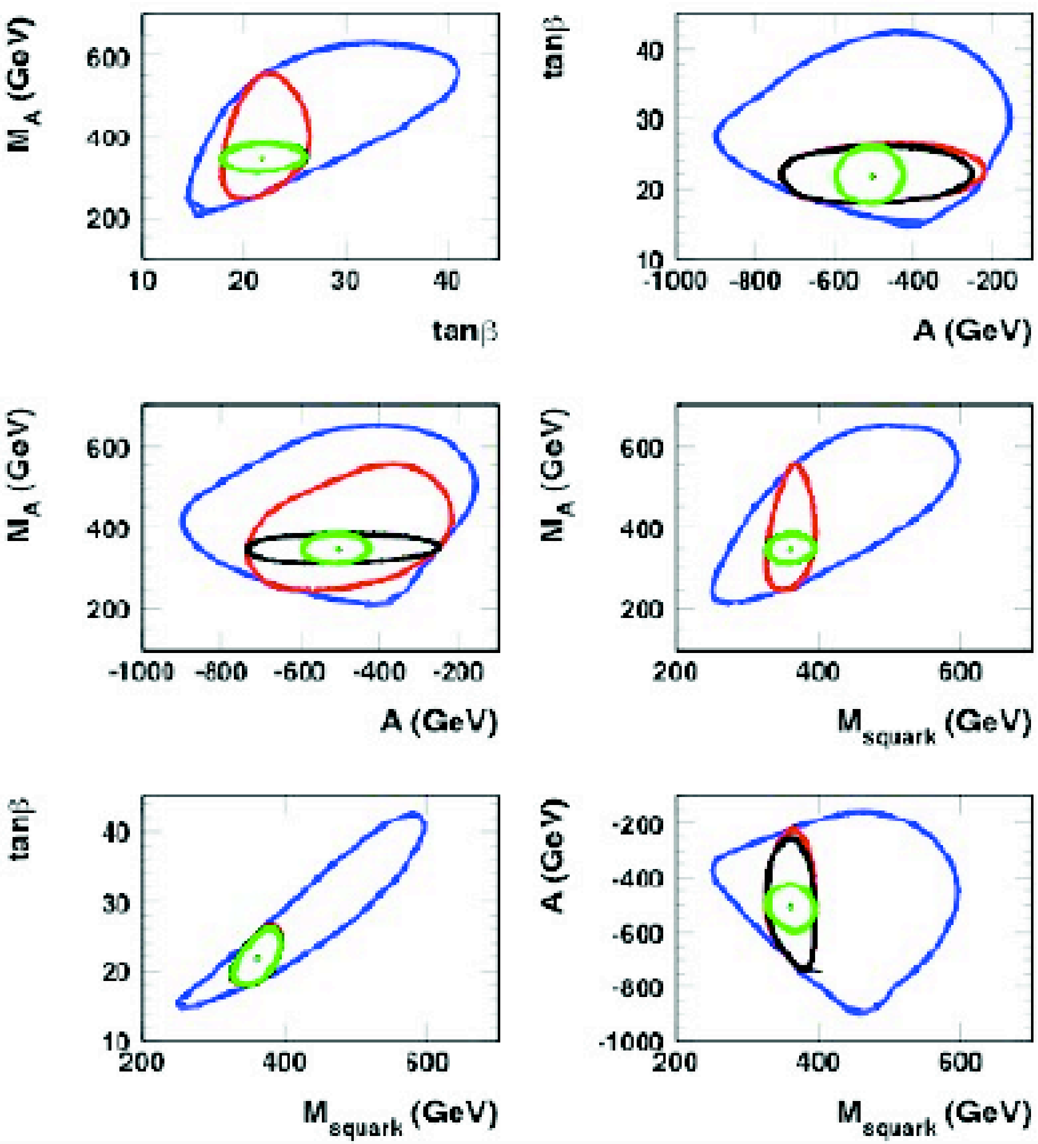


This nicely illustrates the potential of external constraints to restrict the allowed MSSM parameter space

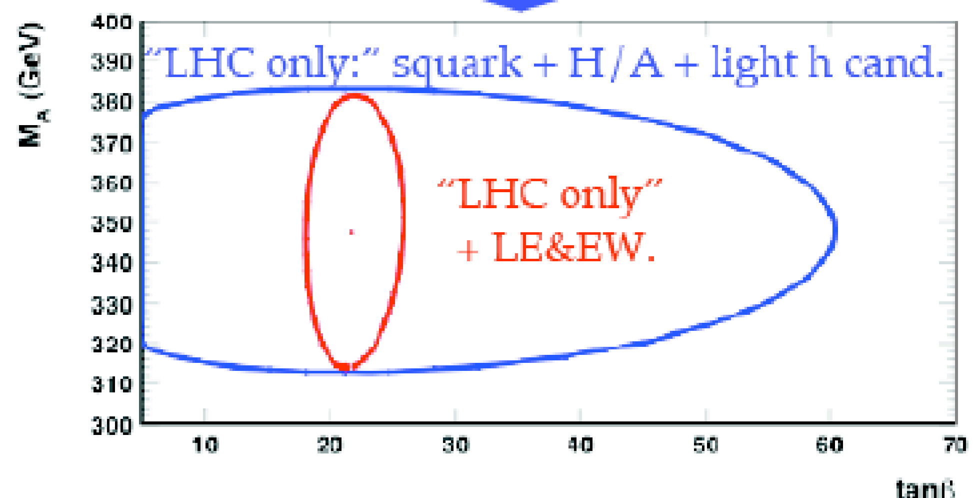
2009 scenario



Documented in LHC Flavour Workshop - Yellow Report



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

Some recent work on the interplay of collider and flavour physics:

- Interplay between $H \longrightarrow b\bar{s}$ and $b \longrightarrow s\gamma$
  Hahn,Hollik,Illana,Penaranda,hep-ph/0512315

- Production and FCNC decay of supersymmetric Higgs bosons into heavy quarks
  Bejar,Guasch,Sola,hep-ph/0508043

- Challenges for MSSM Higgs searches at Hadron Colliders
  Carena,Menon,Wagner,hep-ph/07041143

- Many other studies in the Yellow Report

Follow-up workshop:

Working Group on the Interplay Between Collider and Flavour Physics

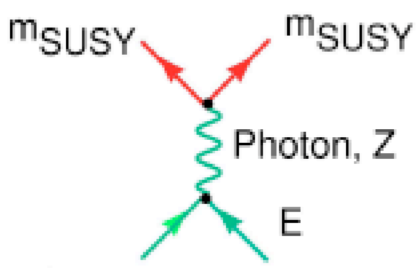
The working group addresses the complementarity and synergy between the LHC and the flavour factories within the new physics search. New collaborations on this topic were triggered by the two recent CERN workshop series Flavour in the Era of the LHC and CP Studies and Non–Standard Higgs Physics at the border line of collider and flavour physics and experiment and theory. This follow–up working group wants to provide a continuous framework for such collaborations and trigger new research work in this direction. Regular meetings at CERN (well–connected by VRVS) are planned in the near future.

Forthcoming event: Flavour day in Les Houches 16. June

https://twiki.cern.ch/twiki/bin/view/Main/ColliderAndFlavour

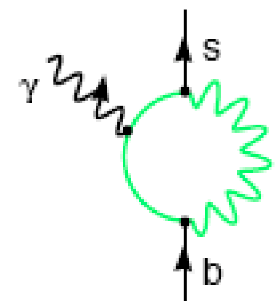
Analysis of new physics via

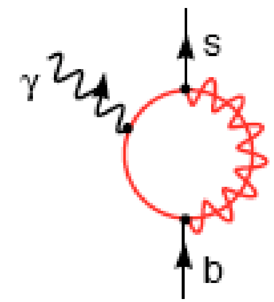
1) energy frontier gauge sector, EWSB

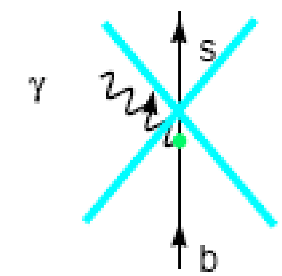


LHC,superLHC,ILC,CLIC,...

2) luminosity frontier flavour sector







Experiments on neutrinos, charged leptons, quarks (sLHCb, upgraded B factories, kaons)

We have to keep both options open!

Flavour problem, origin of neutrino masses, new sources of CP violation, $g-2$, EDM, lepton flavour violation, relation of flavour structure in the lepton and quark sectors, tau decays

Experimental evidence beyond SM:

Dark Matter

Neutrino masses

Baryon asymmetry of the Universe

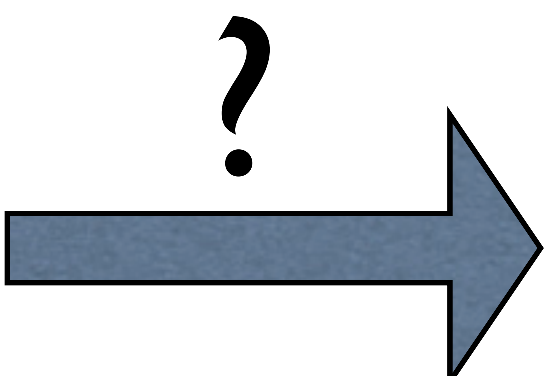
Dave Hitlin has written in the CDR :

Introduction

Elementary particle physics in the next decade will be focused on the investigation of the origin of electroweak symmetry breaking and the search for extensions of the Standard Model (SM) at the TeV scale. The discovery of New Physics will likely produce a period of excitement and progress recalling the years following the discovery of the J/ψ. In this new world, attention will be riveted on the detailed elucidation of new phenomena uncovered at the LHC; these discoveries will also provide strong motivation for the construction of the ILC. High statistics studies of heavy quarks and leptons will have a crucial role to play in this new world.

Glashow Iliopoulos Maiani Mechanism

PRD 2, 1285 (1970)



November Revolution 1974

J/ψ **Discovery at SLAC and Brookhaven**

A good reflection of the various ideas after the discovery:

INFORMAL NOTES - not for publication.
November 27, 1974

SLAC-PUB-1514
December 1974

ΨCHOLOGY

Haim Harari
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and
Weizmann Institute of Science
Rehovot, Israel

The yet not discovered tau complicated the interpretation.

Lettere al Nuovo Cimento 11, 609 (1974) :

Is the 3104 MeV Vector Meson the φ_c or the W_0?

G. ALTARELLI, N. CABIBBO and R. PETRONZIO

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

L. MAIANI

Laboratori di Fisica, Istituto Superiore di Sanità - Roma
Istituto Nazionale di Fisica Nucleare - Sezione Sanità di Rom

G. PARISI

Istituto Nazionale di Fisica Nucleare - Laboratorio di Frascati

(ricevuto il 20 Novembre 1974)

Lettere al Nuovo Cimento 11, 609 (1974) :

The exciting discovery [1,2] of a new neutral vector meson at a mass $M = 3104$ MeV [2], confirmed at Frascati [3], is a turning point in our understanding of fundamental interactions. Waiting for more definite experimental information, we shall base our discussion on the following values for the decay rates:

(1) $$\Gamma_e (= \Gamma_\mu) = 5 \text{ keV} ,$$

(2) $$\Gamma_{\text{total}} \simeq \Gamma_h = 50 \text{ keV} ,$$

A more exciting alternative, strongly suggested by eqs. (1) and (2), is to identify this particle with the intermediate boson which mediates weak neutral currents (W_0).

* * *

We are grateful to the members of the experimental and machine groups of the Frascati National Laboratories for many exciting discussions. We are also grateful to the Administration of the Telephone Service in Italy and abroad for efficiently conveying the many exciting rumours about Brookhaven and SPEAR results.

Little Lesson for the LHC Era :

Do not focus only on the gauge sector !

Never forget about flavour !