Interplay of high-p_T and flavour physics

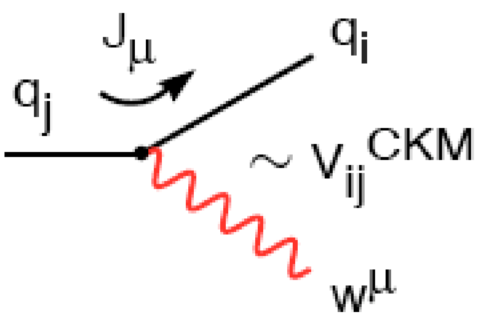
brief report on CERN activities

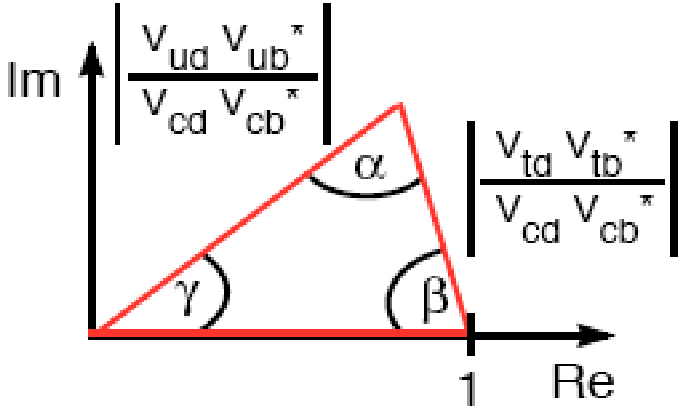
Tobias Hurth (CERN, SLAC)

1st Open Meeting of the SuperKEKB Collaboration,
KEK 10.-12. December 2008

Flavour in the SM

CKM mechanism of flavour mixing and CP violation: $V_{\rm CKM}$, $J_{\rm CKM}$





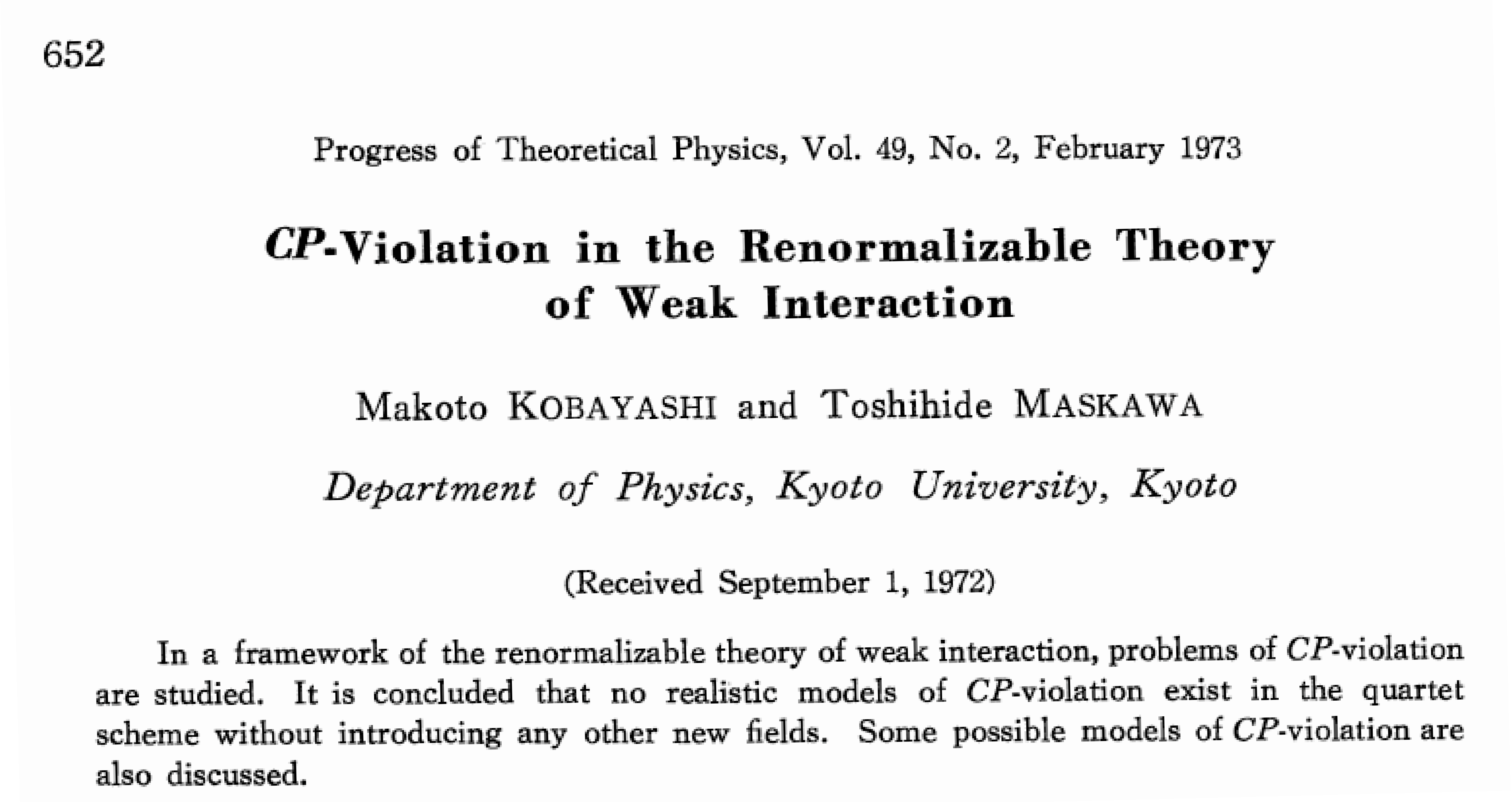
$$Im[V_{ij}\,V_{kl}\,V_{il}^*\,V_{kj}^*] = J_{\rm CKM} \sum_{m,n=1}^{3} \epsilon_{ikm}\,\epsilon_{jln} \qquad\qquad J_{\rm CKM} \sim \mathcal{O}(10^{-5})$$

All present measurements (BaBar, Belle, CLEO, CDF, D0,....)
of rare decays ($\Delta F = 1$),
of mixing phenomena ($\Delta F = 2$) and
of all CP violating observables at tree and loop level
are consistent with the CKM theory.

Impressing success of SM and CKM theory !!

Nobel Prize 2008

From left, Yoichiro Nambu, Makoto Kobayashi and Toshihide Masukawa, who shared the Nobel Prize in Physics on Tuesday



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Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

However,...

- CKM mechanism is the dominating effect for CP violation and flavour mixing in the quark sector;

  but there is still room for sizable new effects and new flavour structures (the flavour sector has only be tested at the 10% level in many cases).

- The SM does not describe the flavour phenomena in the lepton sector.

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge}(A_i, \psi_i) + \mathcal{L}_{Higgs}(\Phi, \psi_i, v)$$

- Gauge principle governs the gauge sector of the SM.

- No guiding principle in the flavour sector:

  CKM mechanism (3 Yukawa SM couplings) provides a phenomenological descripton of quark flavour processes, but leaves significant hierarchy of quark masses and mixing parameters unexplained.

Many open fundamental questions of particle physics are related to flavour :

- How many families of fundamental fermions are there ?
- How are neutrino and quark masses and mixing angles are generated ?
- Do there exist new sources of flavour and CP violation ?
- Is there CP violation in the QCD gauge sector ?
- Relations between the flavour structure in the lepton and quark sector ?

Flavour problem

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

- SM as effective theory valid up to cut-off scale Λ_{NP}

- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\,d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\,d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\,d)^2 \quad \Rightarrow \quad \Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$$

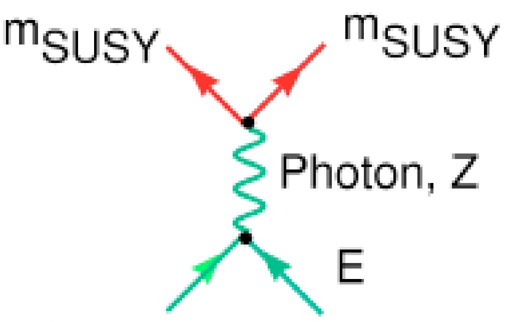
(tree-level, generic new physics)

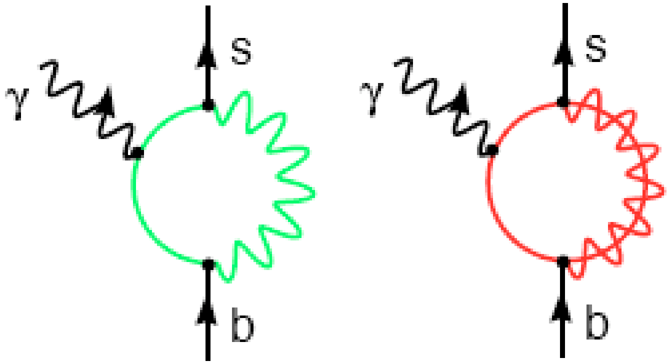
- Natural stabilisation of Higgs boson mass (hierarchy problem)

(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow \quad \Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$

- EW precision data ↔ 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





The indirect information will be most valuable when the general nature of new physics will be identified in the direct search.

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

Flavour@high-p_T

⇒ CERN workshop on the interplay of flavour and collider physics
Fleischer,Hurth,Mangano see http://mlm.home.cern.ch/mlm/FlavLHC.html

Flavour in the era of the LHC

a Workshop on the interplay of flavour and collider physics

First meeting:

CERN, November 7-10 2005

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

- 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

Local Organizing Committee

International Advisory Committee

5 meetings between 11/2005 and 3/2007   Yellow Report

arXiv:0801.1800 [hep-ph] “Collider aspects of flavour physics at high Q”

arXiv:0801.1833 [hep-ph] “B, D and K decays”

arXiv:0801.1826 [hep-ph] “Flavour physics of leptons and dipole moments”

published in EPJC 57 (2008) 1-492

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.

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

Kick-off meeting 3.-4.December 2007 at CERN

http://indico.cern.ch/conferenceDisplay.py?confId=22180

Next meeting 16.-18. of March 2009 at CERN

Flavour@high-p_T interplay: some spotlights

Can **ATLAS/CMS** exclude MFV ?

Can we ignore flavour when analysing possible new physics at the electroweak scale?

Example: Supersymmetry

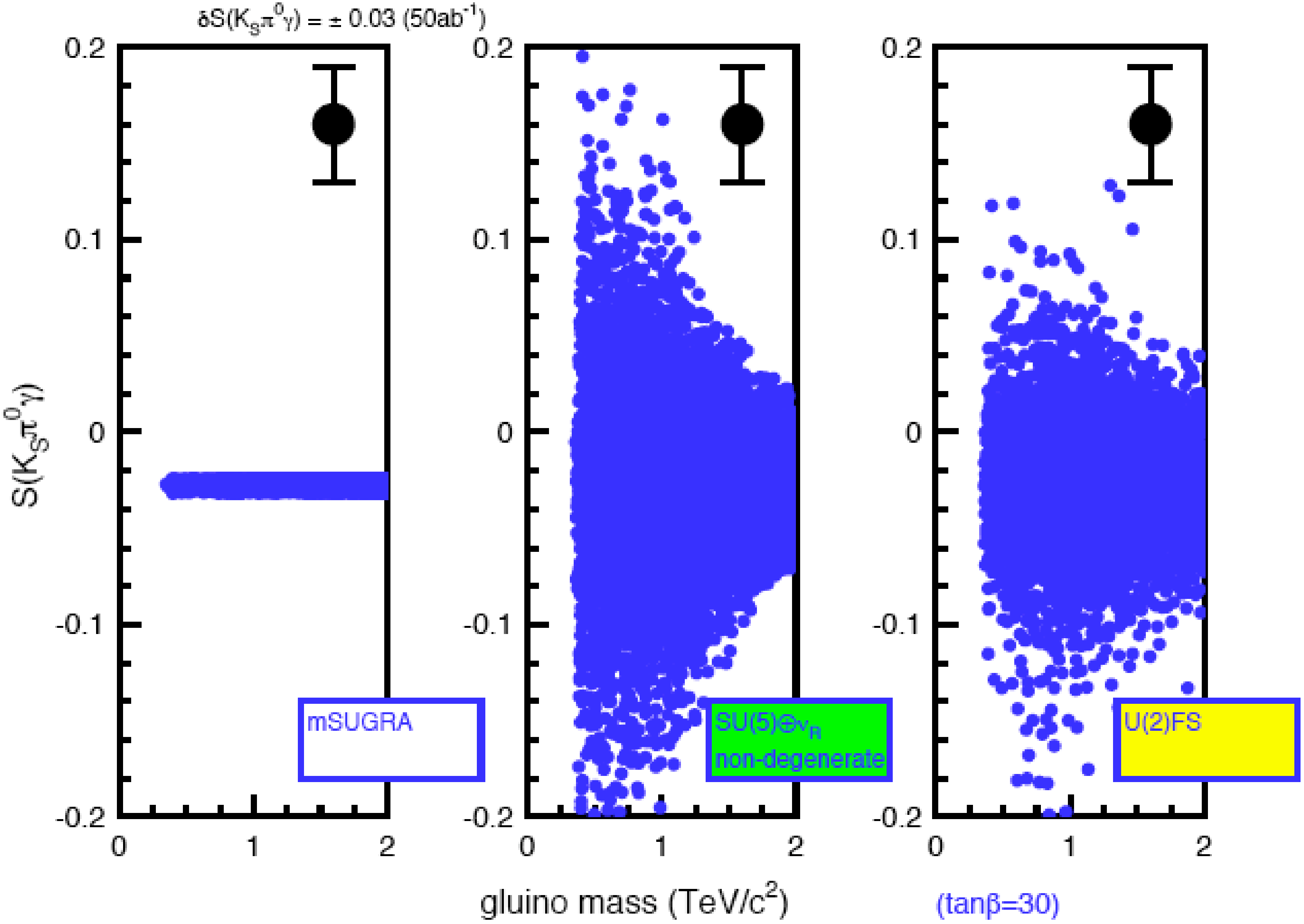
- In the general MSSM too many contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix

- Possible solutions:
  - Decoupling: Sfermion mass scale high
    (i.e. split supersymmetry)
  - Super-GIM: Sfermion masses almost degenerate
    (i.e. gauge-mediated supersymmetry breaking)
  - Alignment: Sfermion mixing suppressed

- Dynamics of flavour $\leftrightarrow$ mechanism of SUSY breaking
  ($BR(b \to s\gamma) = 0$ in exact supersymmetry)

⇒ Discrimination between various SUSY-breaking mechanism

Goto,Okada,Shindou,Tanaka,arXiv:0711.2935



● Expected Super-B sensitivity ($50ab^{-1}$)

Study lepton flavour at the LHC

Feng,Lester,Nir,Shadmi,arXiv:0712.0674

Consider degeneracy and alignment beyond MFV

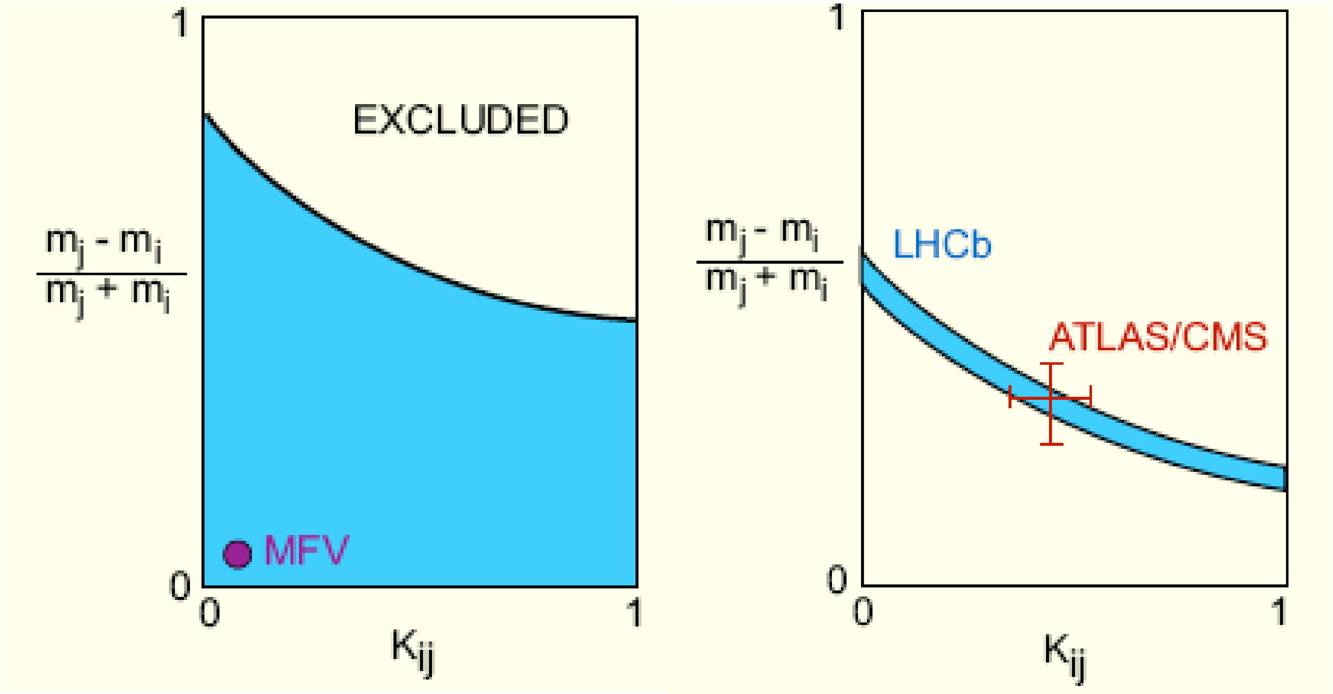
Natural Susy models span a large allowed area in the $(\Delta m^2_{ij}, K_{ij})$ plane.

(mass-squared splitting of slepton generations versus their mixing)

FCNC lead to upper bounds for $\Delta m^2_{ij} \times K_{ij}$ only,

$BR(\mu \to e\gamma) \le 1.2 \times 10^{-11}$, $BR(\tau \to e\gamma) \le 1.1 \times 10^{-7}$, $BR(\tau \to \mu\gamma) \le 6.8 \times 10^{-8}$;

while ATLAS/CMS can constrain either or both of the factors.



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)

- 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

- The usefulness of MFV-bounds/relations is obvious; any measurement beyond those bounds indicate the existence of new flavour structures

  $\Delta F = 2$ UTfit,arXiv:0707.0636 $\Delta F = 1$ H.,Isidori,Kamenik,Mescia,arXiv:0807.5039

$\Rightarrow$ **within supersymmetry: constrained MSSM**

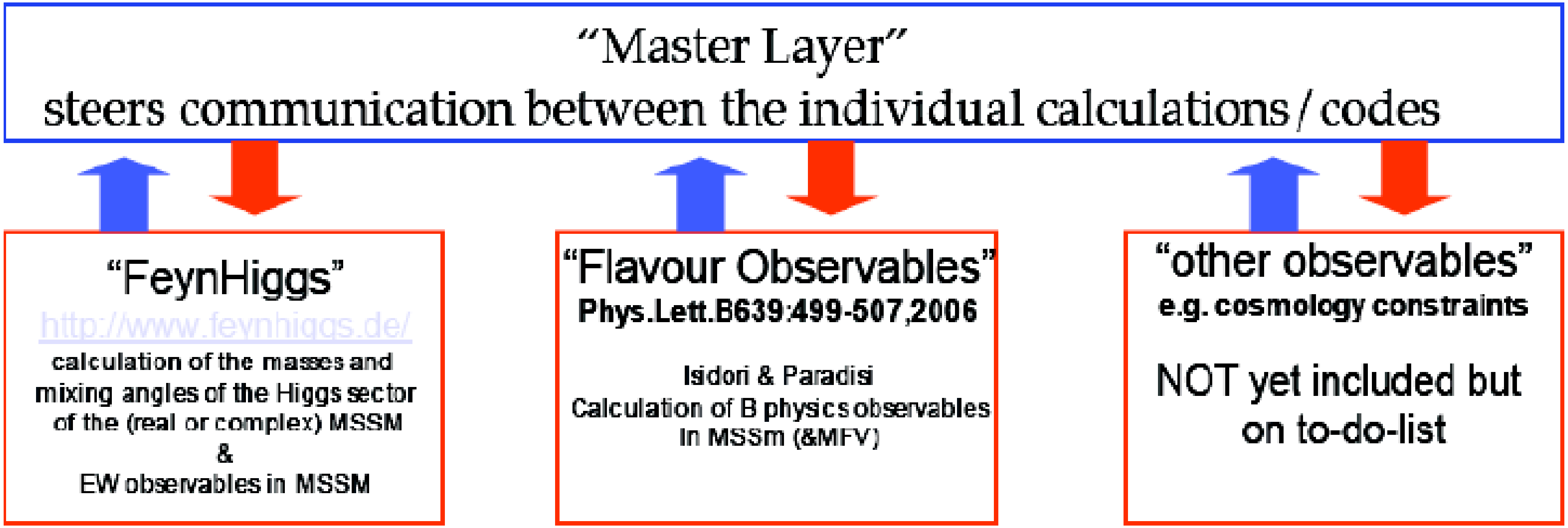
Flavour constraints in the cMSSM

Ronga et al., arXiv:0801.1833

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

tanβ	- 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

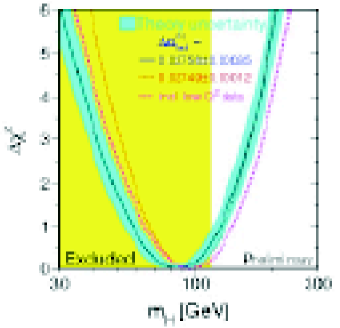
S.Heinemeyer, G.I., P.Paradisi [TH],
O. Buchmuller, R. Cavanaugh,... [EXP]
work documented in the Yellow Report

Scan MSSM parameter space as function of M_h:

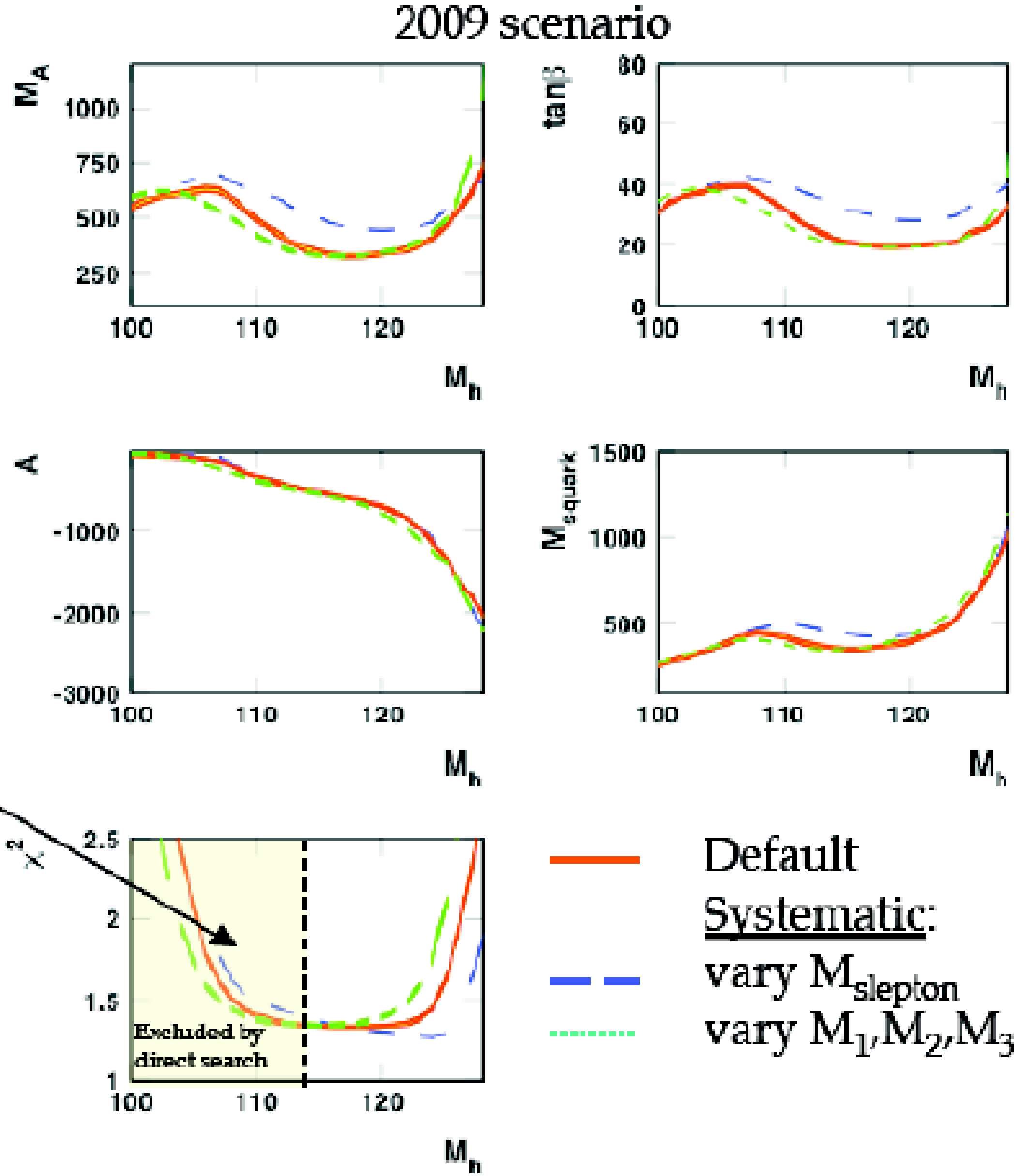
Determine for a given M_h the MSSM parameter set that minimizes the χ^2.

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

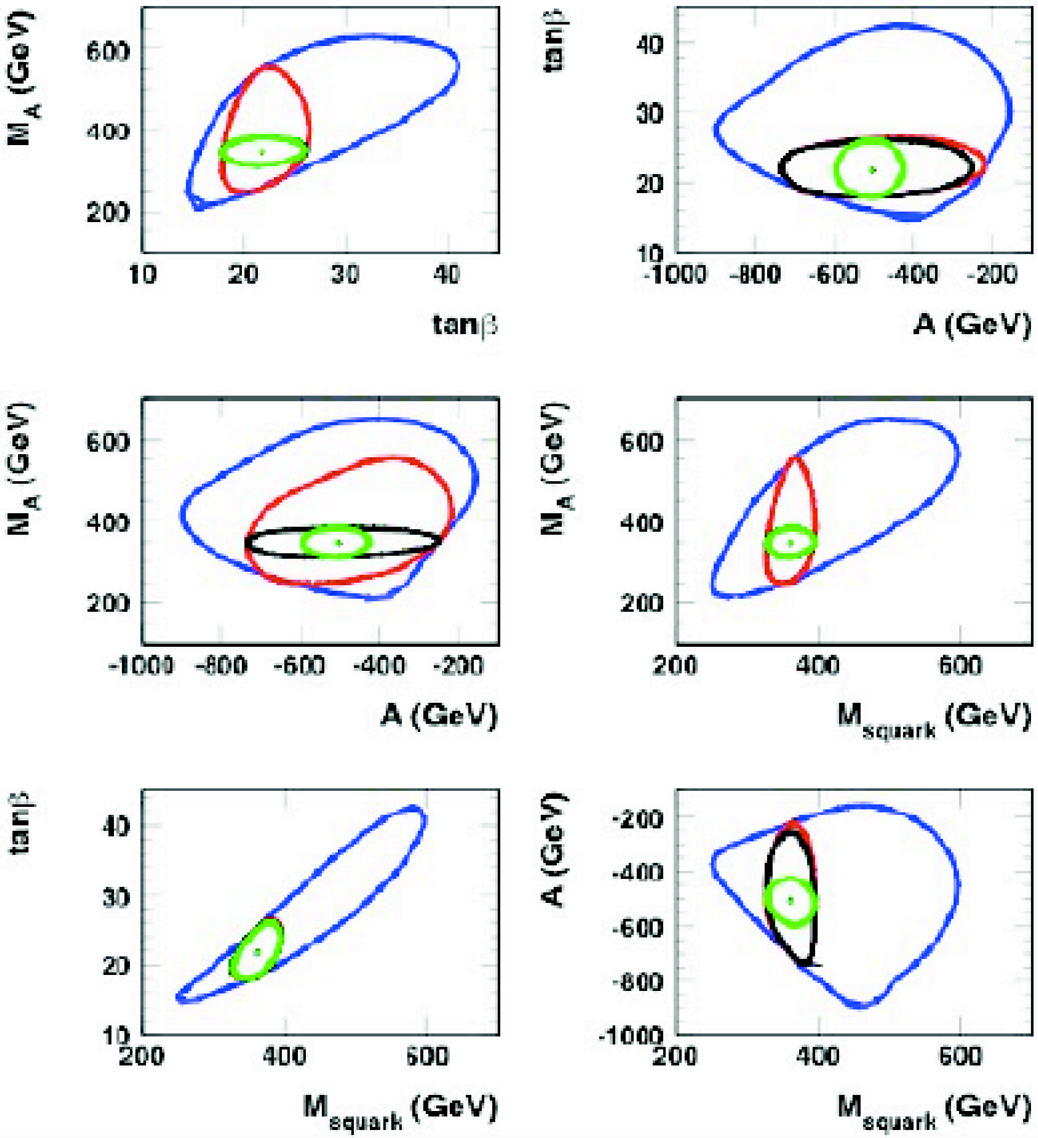
Comparison: SM Fit



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



Documented in LHC Flavour Workshop - Yellow Report



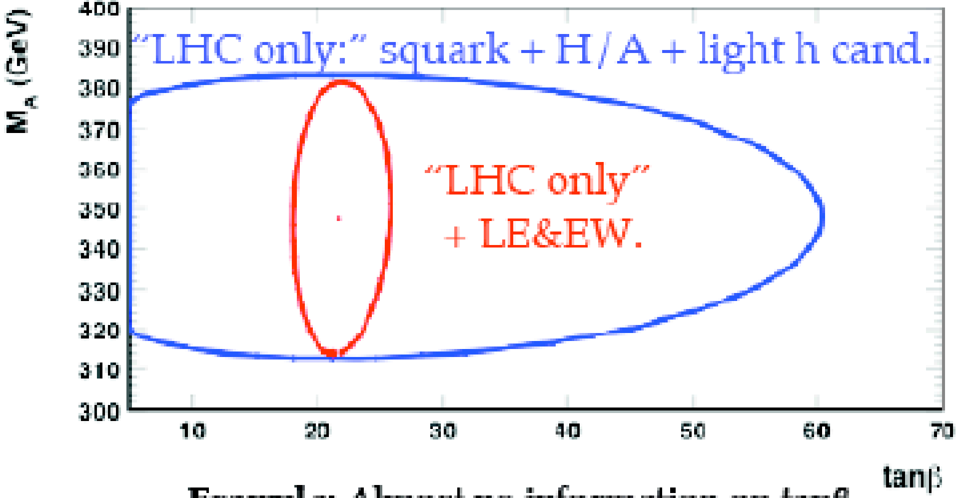
🟦 LE&EW: low-energy (LE) and EW constraints

🟥 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



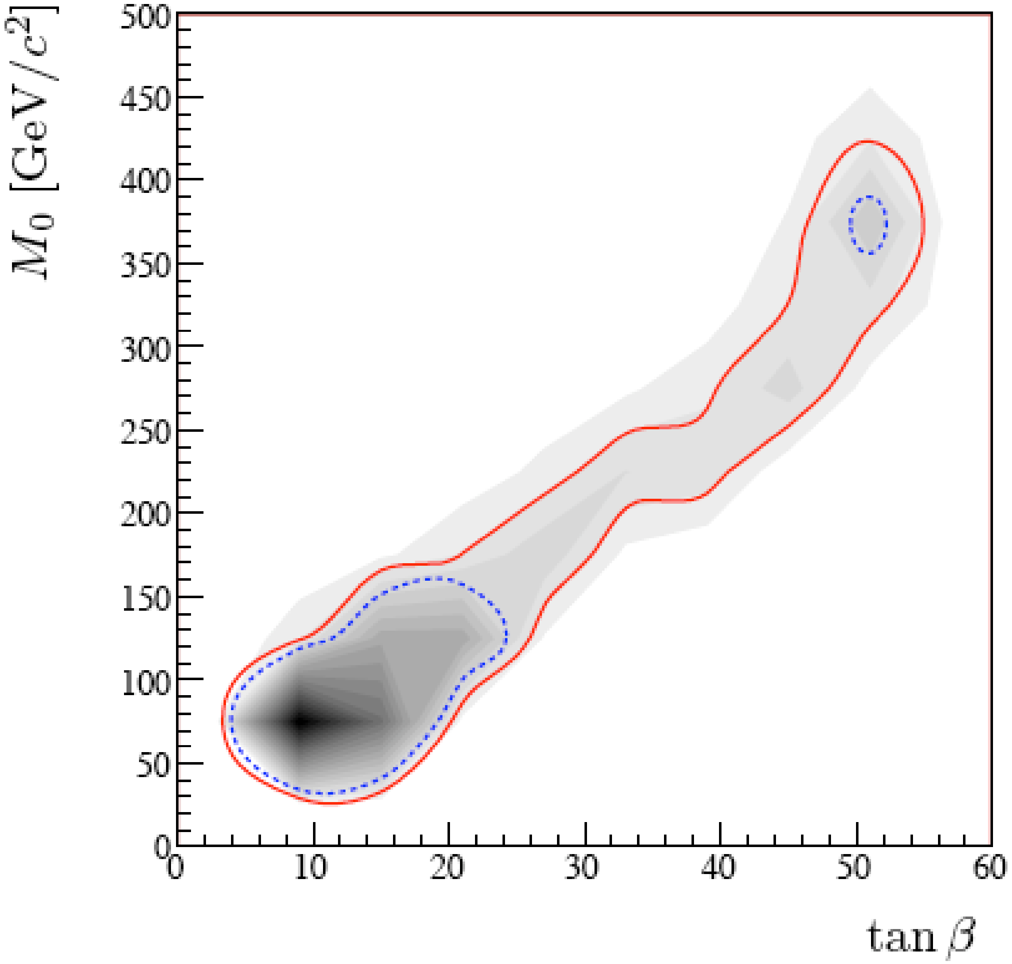
Example: Almost no information on tanβ without external constraints. Note that a direct measurement of tanβ is very difficult at the LHC

Illustrative Example

More flavour constraints in the cMSSM

Weiglein et al,arXiv:0707.3447

Multi-parameter χ^2 fit for all CMSSM parameters, $M_0, M_{1/2}, A_0, \tan\beta$



68% (dotted) and

95% (solid) CL

Constraints on the lightest Higgs boson mass

$$m_{\mathrm{h}}^{\mathrm{CMSSM}} = 110^{+8}_{-10}\ (\mathrm{exp.}) \pm 3\ (\mathrm{theo.})\ \mathrm{GeV}/c^2$$

no restriction on m_h
imposed in the fit

Quark flavour at ATLAS/CMS

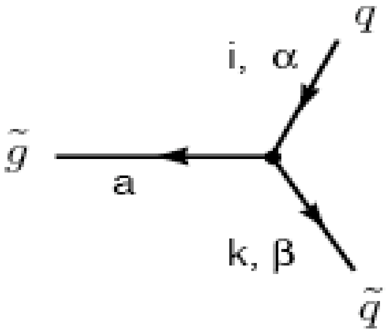
- Flavour-violating squark and gluino decays

H.,Porod,hep-ph/0311075
arXiv:0801.1800

Squark decays: $\tilde{u}_i \rightarrow u_j \tilde{\chi}^0_k\,,\ d_j \tilde{\chi}^+_l \qquad \tilde{d}_i \rightarrow d_j \tilde{\chi}^0_k\,,\ u_j \tilde{\chi}^-_l$

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

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



- 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, $m_{\tilde{t}_1} = 400$ 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.

$\tilde g$	$\tilde d_1 s$	$\tilde d_1 b$	$\tilde d_2 s$	$\tilde d_2 b$	$\tilde d_3 d$	$\tilde d_4 s$	$\tilde d_5 d$	$\tilde d_6 s$	$\tilde d_6 b$
	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			

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

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

Squarks can have large flavour-violating decay modes (10% – 20%),

which are compatible with present constraints from flavour physics.

This can complicate determination of sparticle masses:

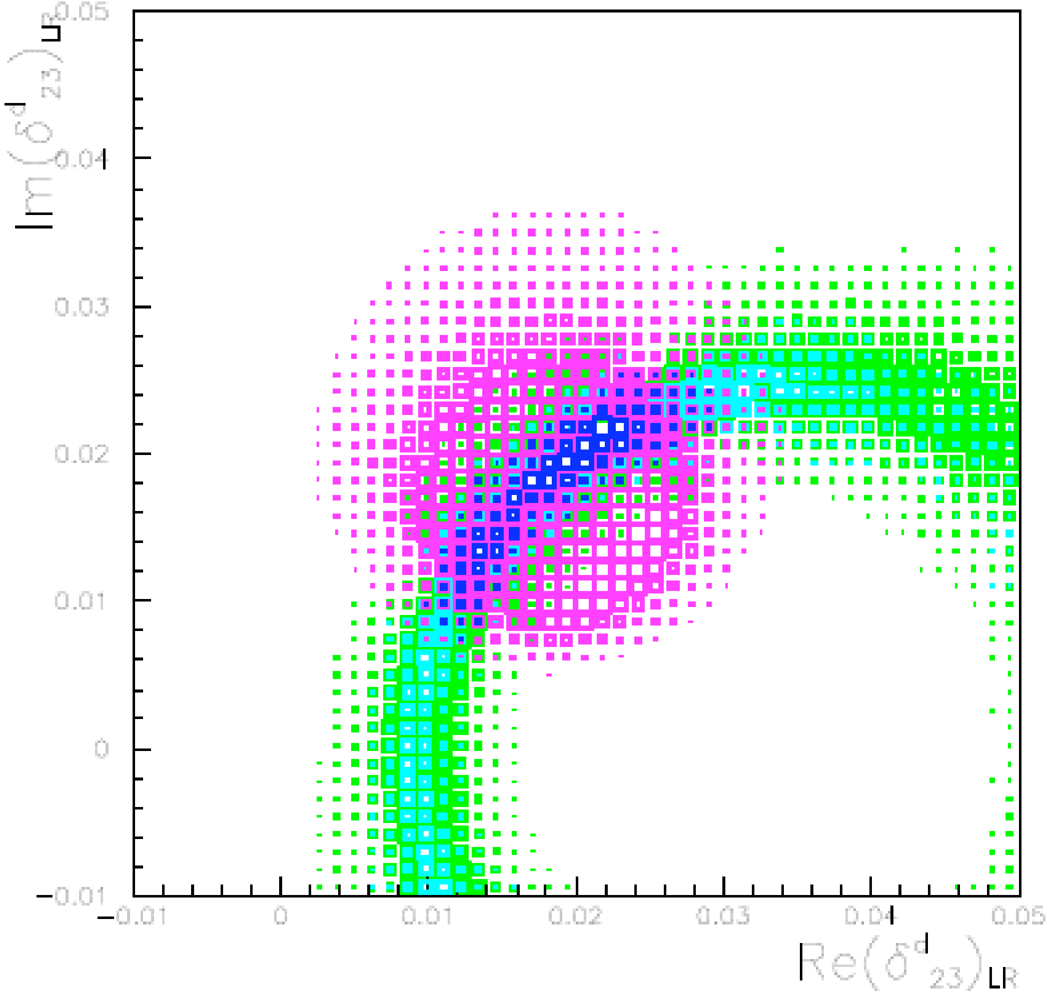
$$\tilde{g} \to b\tilde{b}_j \to b\bar{b}\tilde{\chi}^0_k$$

Again: flavour-tagging at LHC important, but difficult

Additional information from ILC or from Superflavour factory needed !

Sensitivity of Superflavour factory:

Browder,Ciuchini,Gershon,Hazumi,H.,Okada,Stocchi arXiv:0710.3799



Flavour-violating parameter $Re(\delta^d_{23})_{LR} \times Im(\delta^d_{23})_{LR}$

Fig. 8: Density plot of the region in the $\mathrm{Re}(\delta^d_{23})_{LR}$–$\mathrm{Im}(\delta^d_{23})_{LR}$ for $m_{\tilde{q}} = m_{\tilde{g}} = 1$ TeV generated using SFF measurements. Different colours correspond to different constraints: $\mathcal{B}(B \to X_s\gamma)$ (green), $\mathcal{B}(B \to X_s\ell^+\ell^-)$ (cyan), $A_{CP}(B \to X_s\gamma)$ (magenta), all together (blue). Central values of constraints corresponds to assuming $(\delta^d_{23})_{LR} = 0.028e^{i\pi/4}$.

Flavour-violating parameter $Re(\delta^d_{13})_{LL} \times Im(\delta^d_{13})_{LL}$

Bona et al.,arXiv:0709.0451

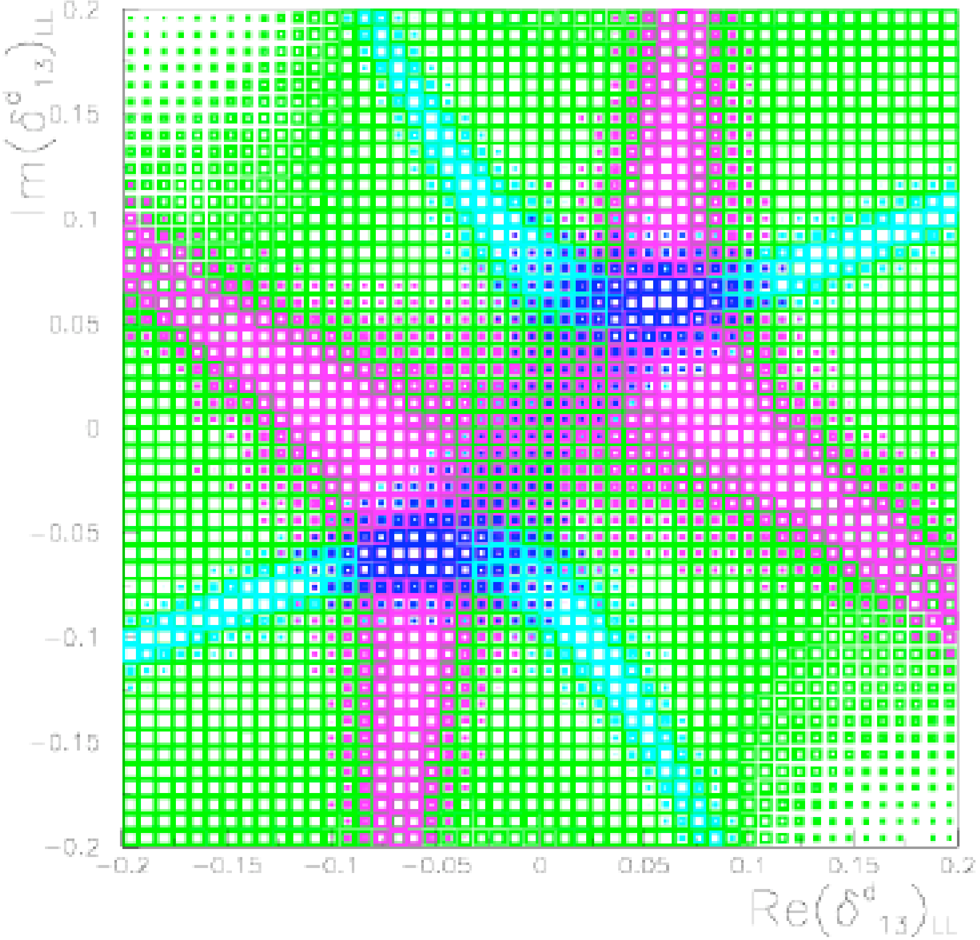
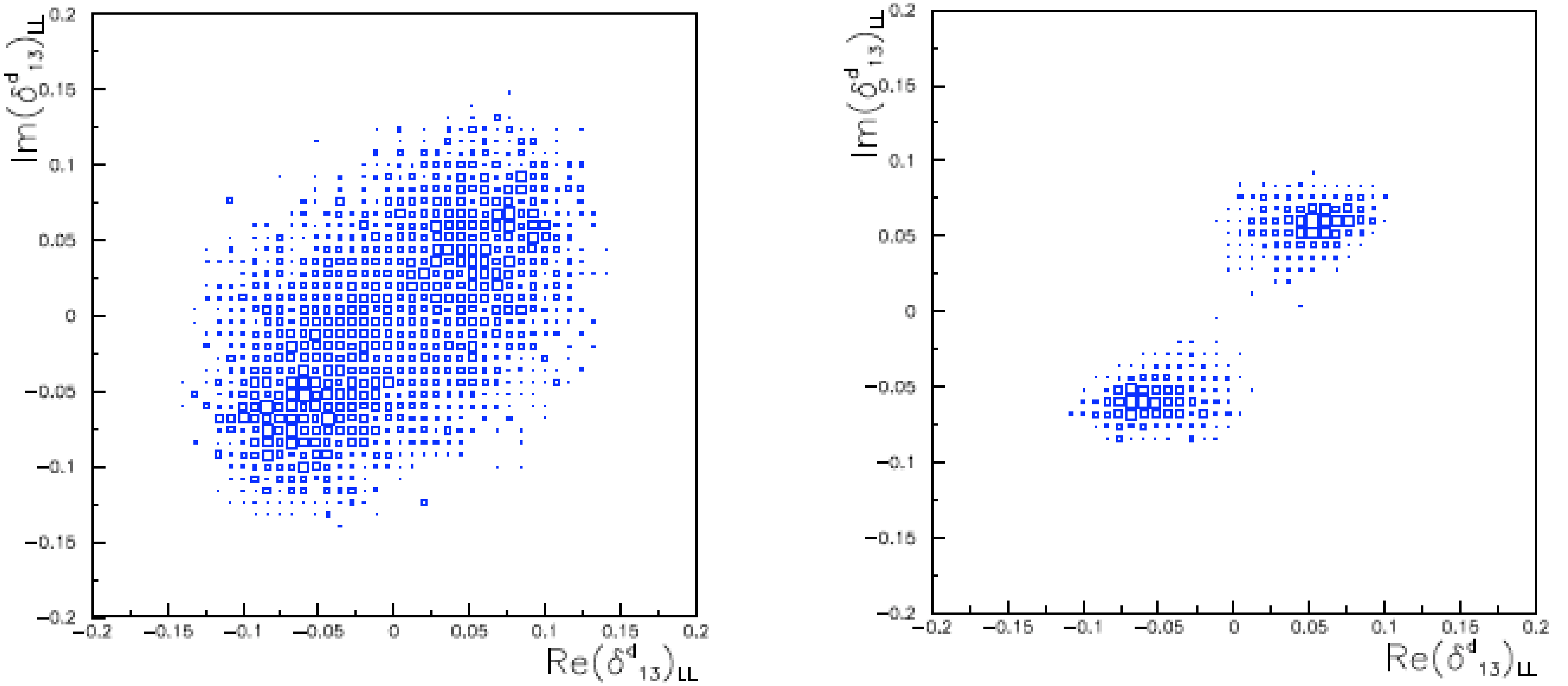


Figure 2-13. *Density plot of the selected region in the* Re $(\delta^d_{13})_{LL}$–Im $(\delta^d_{13})_{LL}$ *for* $m_{\tilde{q}} = m_{\tilde{g}} = 1$ TeV *and* $(\delta^d_{13})_{LL} = 0.085 e^{i\pi/4}$ *using* Super*B measurements. Different colours correspond to different constraints:* $A^d_{\rm SL}$ *(green),* β *(cyan),* Δm_d *(magenta), all together (blue).*

Hitlin et al.,arXiv:0810.1312

Comparison

$10ab^{-1}$ $50ab^{-1}$



$Re(\delta^d_{13})_{LL} \times Im(\delta^d_{13})_{LL}$

- **Probing Minimal Flavour Violation at the LHC**

Grossman,Nir,Thaler,Volansky,Zupan,arXiv:0706.1845

To an accuracy of $\mathcal{O}(0.05)$

$$V_{\rm LHC}^{\rm CKM} = \begin{pmatrix} 1 & 0.23 & 0 \\ -0.23 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

New particles (i.e. heavy vector-like quarks) that couple to the SM quarks decay to either 3rd generation quark, or to non-3rd generation quark, but not to both.

If ATLAS/CMS measures $BR(q_3) \sim BR(q_{1,2})$ then this excludes MFV.

MFV prediction for events with B' pair production:

$$\frac{\Gamma(B'\overline{B'} \to X q_{1,2} q_3\,)}{\Gamma(B'\overline{B'} \to X q_{1,2} q_{1,2}\,) + \Gamma(B'\overline{B'} \to X q_3 q_3\,)} \lesssim 10^{-3}$$

Flavour tagging efficiencies are crucial.

Many more analyses on the high-p_T@flavour interplay can be found in the three reports

arXiv:0801.1800 [hep-ph] “Collider aspects of flavour physics at high Q”

arXiv:0801.1833 [hep-ph] “B, D and K decays”

arXiv:0801.1826 [hep-ph] “Flavour physics of leptons and dipole moments”

published in EPJC 57 (2008) 1-492

Next meeting of the interplay working group at CERN:

16.-18.03.2009

Please feel cordially invited !

Two final remarks:

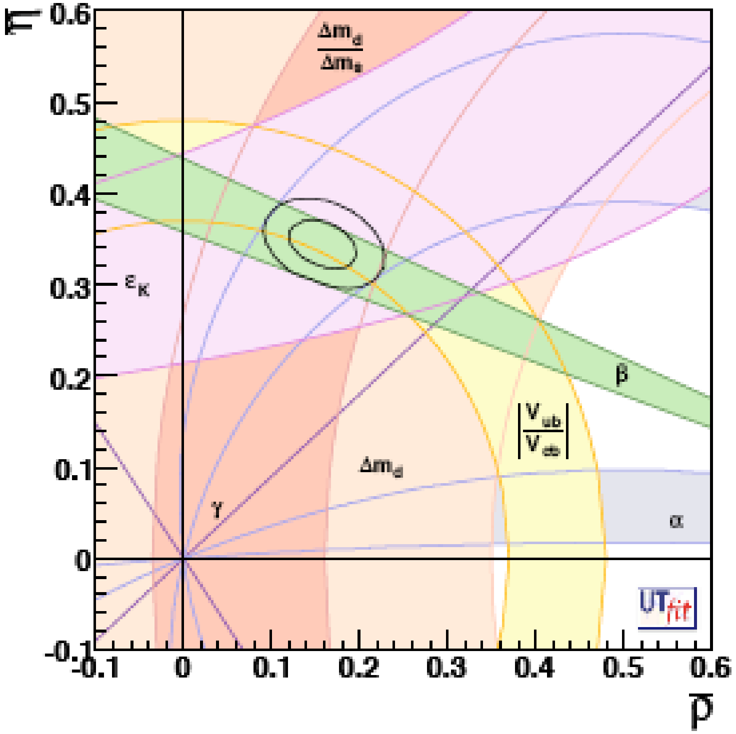
- **Experimental evidence beyond SM:**
  - Dark matter (visible matter accounts for only 4% of the Universe)
  - Neutrino masses (Dirac or Majorana masses ?)
  - Baryon asymmetry of the Universe (new sources of CP violation needed)

At least two of them have to do with flavour !

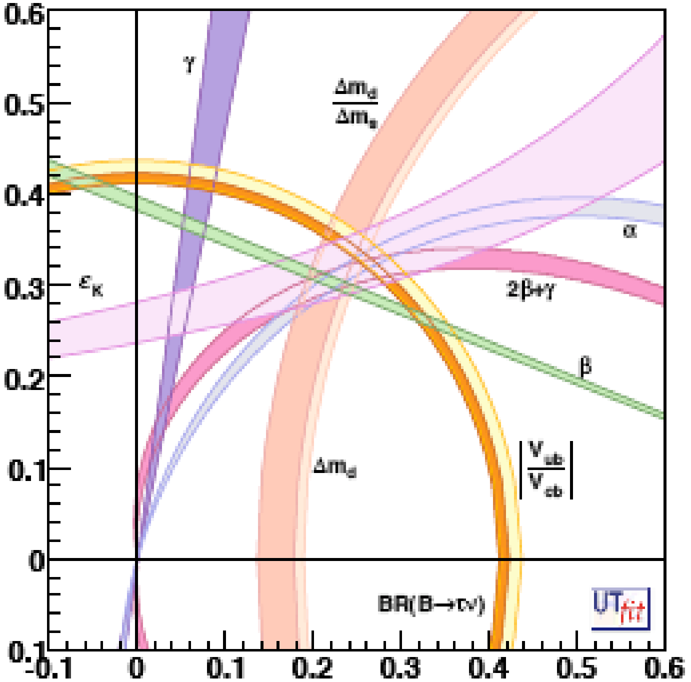
- Superflavour factory: CKM theory gets tested at 1%

arXiv:0710.3799

Today



'the dream'



'the nightmare'