FLAVOUR PHYSICS AND THE ROLE OF KAONS

Luca Silvestrini
INFN, Sez. di Roma

- Introduction
- Bottom-up approach: NP in $\Delta F=2$ processes
- Top-down approach: SUSY models
- Conclusions

Thanks to M. Pierini

INTRODUCTION

The Standard Model works beautifully up to a few hundred GeV's, but it must be an effective theory valid up to a scale $\Lambda \leq M_{Planck}$:

$$\mathcal{L}(M_W) = \Lambda^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{1}{\Lambda}\mathcal{L}^5 + \frac{1}{\Lambda^2}\mathcal{L}^6 + \ldots$$

EW scale

Has accidental symmetries

Violates accidental symmetries

INTRODUCTION - II

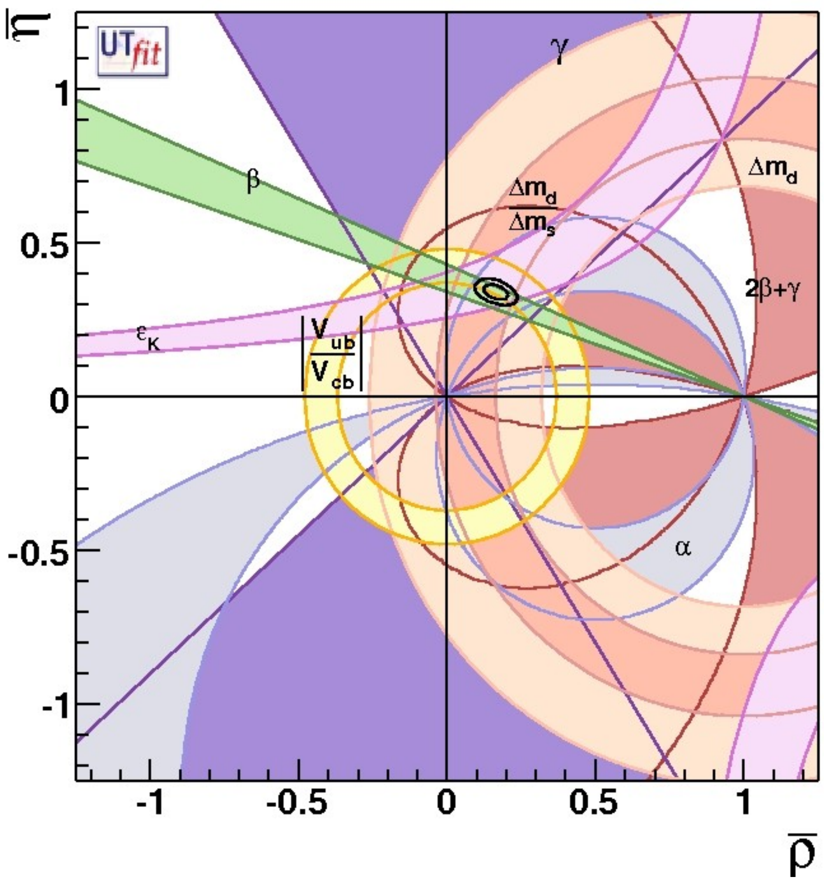
- Flavour symmetry breaking by Yukawa couplings: four fundamental parameters (λ, A, ρ, η) determine all FCNC and CP violating processes
- FCNC and CPV are absent at the tree level and receive finite and calculable loop corrections in the SM (GIM mechanism)
- Operators with D>4 contribute to FCNC & CPV processes and modify the relations and predictions of the SM

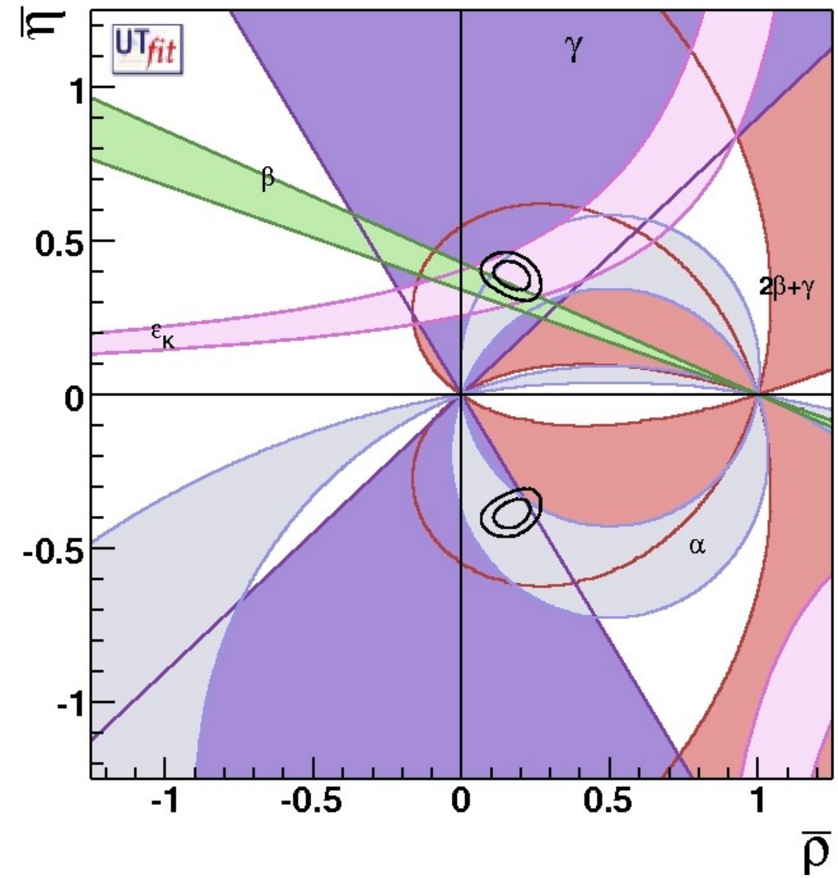
INTRODUCTION - III

- Bottom-up approach:
  - add all possible D>4 operators in a given sector ($\Delta F=2$, $\Delta F=1$, LFV,...) and constrain their coefficients
  - obtain general info on NP flavour structure and constraints on the scale of NP
- Top-down approach:
  - assume a given NP flavour structure (MFV, NMFV, split fermions, U(1), alignment, SU(2), SU(3), A_4,...)
  - determine present bounds on NP parameter space
  - investigate correlations and identify possible signals

BOTTOM-UP APPROACH: $\Delta F=2$

End of SM parameter determination era, begin of precision test era: redundant determination of the triangle with new measurements from B-factories and Tevatron and test of new physics.





Slight disagreement between CP-conserving and CP-violating...

NP IN $\Delta F=2$

Utfit Coll., in progress

- Strategy for $\Delta F=2$ processes:
  1. Determine allowed ranges for NP contributions
  2. Determine allowed ranges for coefficients of higher-dimensional operators
  3. Compute lower bound on NP scale, test NP models

THE GENERALIZED UTA

- Consider ratios of (SM+NP)/SM amplitudes

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\rm eff}^{\rm full} | \bar{B}_q \rangle}{\langle B_q | H_{\rm eff}^{\rm SM} | \bar{B}_q \rangle} = \frac{A_q^{\rm SM} e^{2i\phi_q^{\rm SM}} + A_q^{\rm NP} e^{2i(\phi_q^{\rm SM} + \phi_q^{\rm NP})}}{A_q^{\rm SM} e^{2i\phi_q^{\rm SM}}}$$

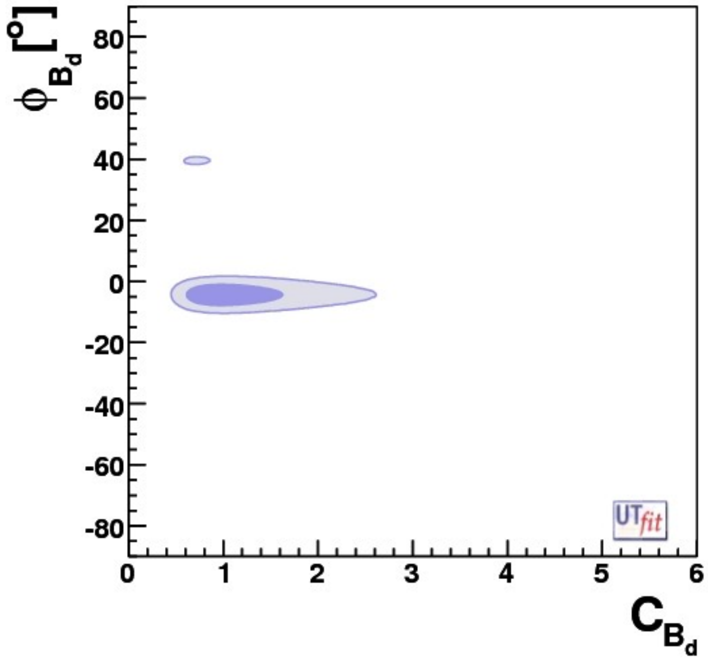
$$C_{\epsilon_K} = \frac{{\rm Im}[\langle K^0 | H_{\rm eff}^{\rm full} | \bar{K}^0 \rangle]}{{\rm Im}[\langle K^0 | H_{\rm eff}^{\rm SM} | \bar{K}^0 \rangle]}\,, \qquad C_{\Delta m_K} = \frac{{\rm Re}[\langle K^0 | H_{\rm eff}^{\rm full} | \bar{K}^0 \rangle]}{{\rm Re}[\langle K^0 | H_{\rm eff}^{\rm SM} | \bar{K}^0 \rangle]}$$

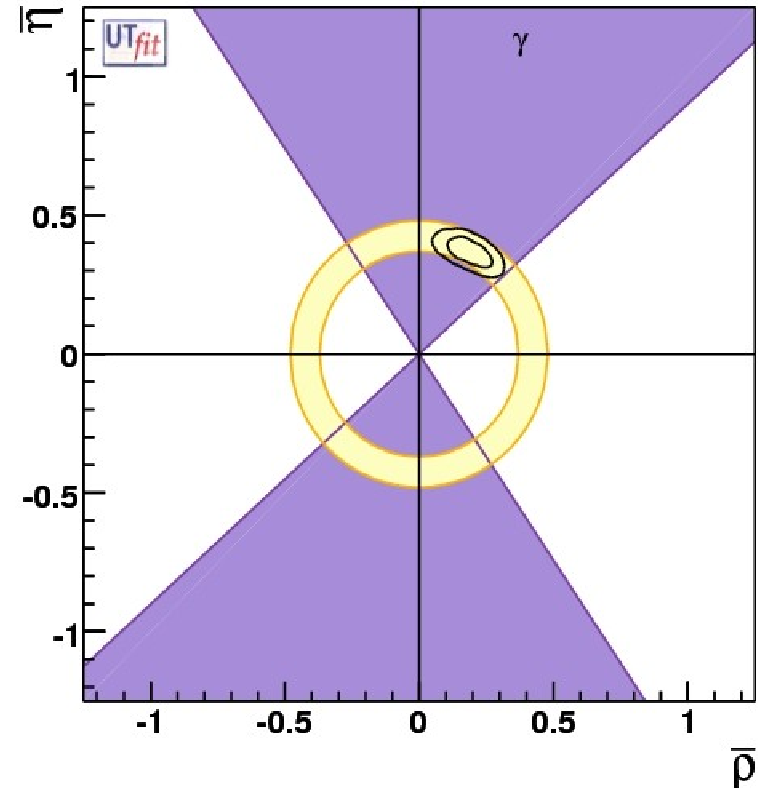
- Determine C's and ϕ's using generalized UT analysis

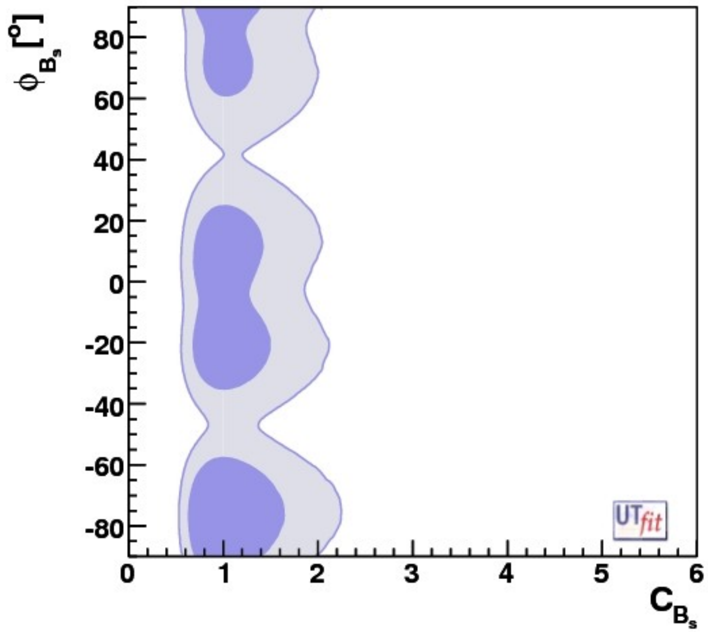
NP parameters & exp constraints

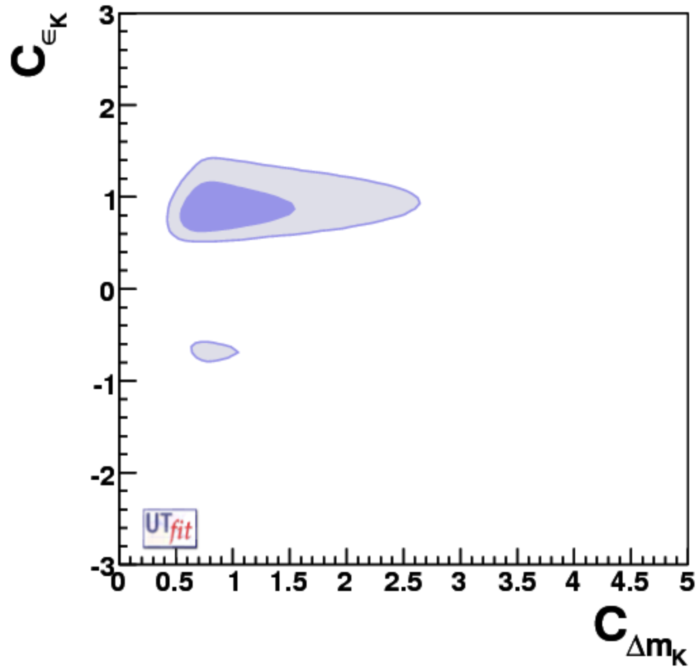
- Angle measurements determine ρ, η and ϕ_{Bd} up to an ambiguity of 180°
- Δm_d, Δm_s, ε & Δm_K fix C_{Bd}, C_{Bs}, C_ε and $C_{\Delta MK}$
- $\Delta\Gamma_s/\Gamma_s$ and $B_s \to J/\psi\phi$ constrain ϕ_{Bs}
- A_{SL}^d and A_{SL}^s suppress the "wrong" solution in the $\rho - \eta$ plane and constrain ϕ_{Bs}

- Using all constraints:









SUMMARY OF CONSTRAINTS

Parameter	Output	Parameter	Output
C_{B_d}	1.04 ± 0.34	$\phi_{B_d}[^\circ]$	-4.4 ± 2.1
C_{B_s}	1.04 ± 0.29	C_{ϵ_K}	0.87 ± 0.14
$\phi_{B_s}[^\circ]$	$-77 \pm 16 \cup -20 \pm 11 \cup 9 \pm 10$		
$\overline{\rho}$	0.169 ± 0.051	$\overline{\eta}$	0.391 ± 0.035
$\alpha[^\circ]$	88 ± 7	$\beta[^\circ]$	25.1 ± 1.9
$\gamma[^\circ]$	67 ± 7	$\mathrm{Im}\lambda_t[10^{-5}]$	15.6 ± 1.3

- Determine coefficients of dimension-6 operators:

$$\mathcal{H}_{\rm eff}^{K-\bar K} = \sum_{i=1}^{5} C_i\, Q_i^{sd} + \sum_{i=1}^{3} \tilde C_i\, \tilde Q_i^{sd}$$

$$\mathcal{H}_{\rm eff}^{D-\bar D} = \sum_{i=1}^{5} C_i\, Q_i^{cu} + \sum_{i=1}^{3} \tilde C_i\, \tilde Q_i^{cu}$$

$$\mathcal{H}_{\rm eff}^{B_q-\bar B_q} = \sum_{i=1}^{5} C_i\, Q_i^{bq} + \sum_{i=1}^{3} \tilde C_i\, \tilde Q_i^{bq}$$

$$\begin{aligned} Q_1^{q_iq_j} &= \bar q_{jL}^\alpha \gamma_\mu q_{iL}^\alpha \bar q_{jL}^\beta \gamma^\mu q_{iL}^\beta , \\ Q_2^{q_iq_j} &= \bar q_{jR}^\alpha q_{iL}^\alpha \bar q_{jR}^\beta q_{iL}^\beta , \\ Q_3^{q_iq_j} &= \bar q_{jR}^\alpha q_{iL}^\beta \bar q_{jR}^\beta q_{iL}^\alpha , \\ Q_4^{q_iq_j} &= \bar q_{jR}^\alpha q_{iL}^\alpha \bar q_{jL}^\beta q_{iR}^\beta , \\ Q_5^{q_iq_j} &= \bar q_{jR}^\alpha q_{iL}^\beta \bar q_{jL}^\beta q_{iR}^\alpha , \end{aligned}$$

- In the SM, only Q_1 is present. Q_{2-5} are RG-enhanced (and chirally-enhanced in K)
$\Rightarrow$ NP models w. $C_{2-5} \neq 0$ more constrained

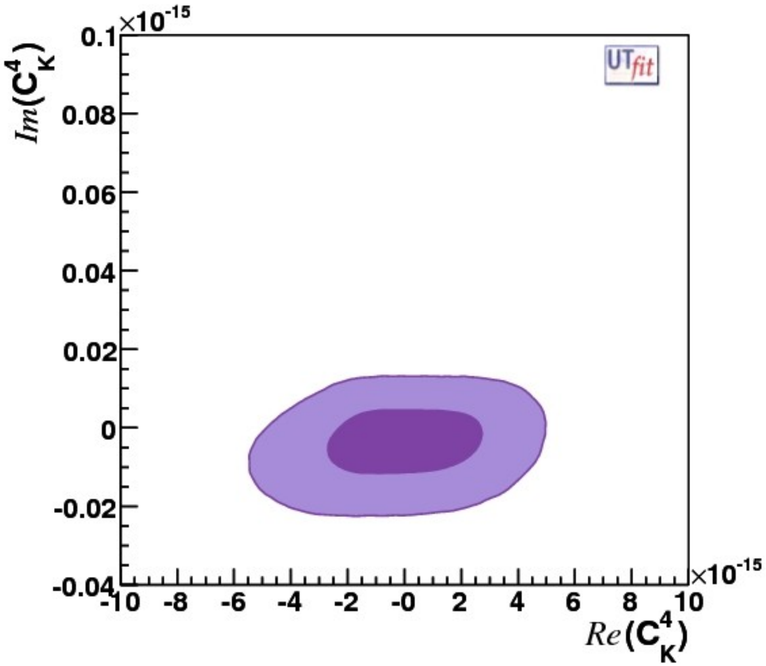
$\mathrm{Im}\, C_K^4 < 2\ 10^{-17}\ \mathrm{GeV}^{-2}$

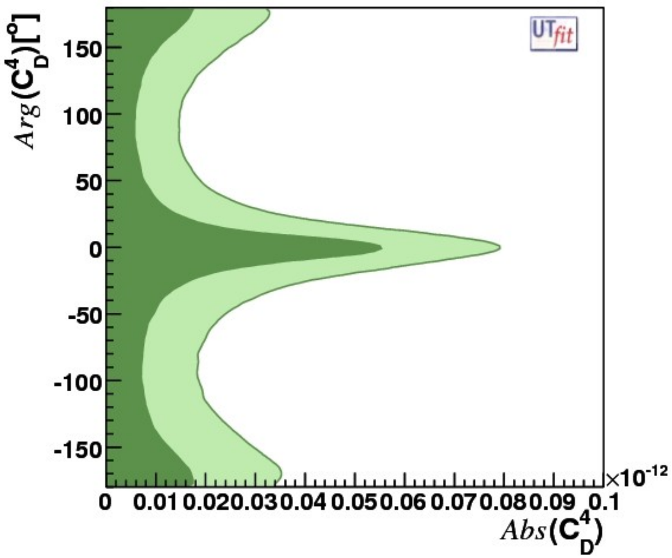
$\mathrm{Re}\, C_K^4 < 3\ 10^{-15}\ \mathrm{GeV}^{-2}$

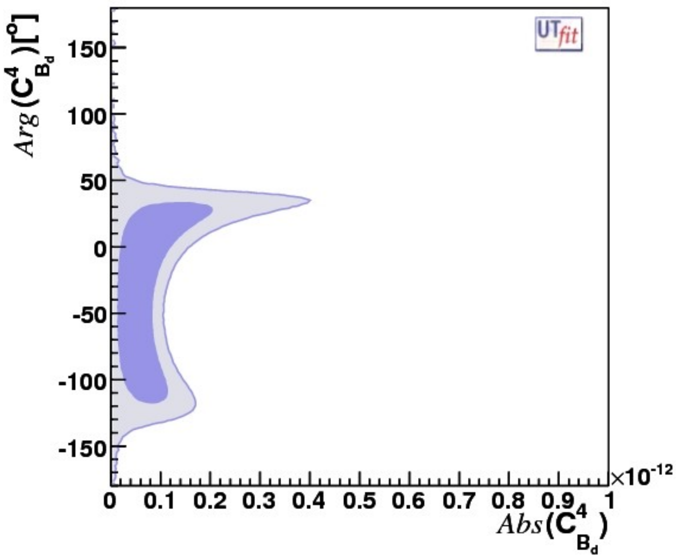
$|C_D^4| < 5\ 10^{-14}\ \mathrm{GeV}^{-2}$

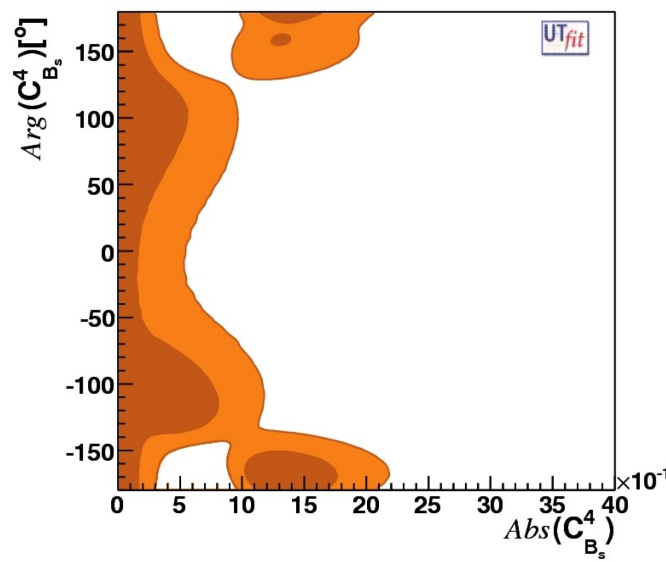
$|C_{Bd}^4| < 2\ 10^{-13}\ \mathrm{GeV}^{-2}$

$|C_{Bs}^4| < 2\ 10^{-11}\ \mathrm{GeV}^{-2}$









Kaons give the strongest constraints, but B-physics + lattice QCD are necessary to exploit the Kaon constraining power!

FROM C's TO THE SCALE OF NP

the NP scale Λ can be defined as $\Lambda = \sqrt{\frac{F_i L_i}{C_i(\Lambda)}}$

- L loop factor:
  - tree-level: $L=1$
  - loop-mediated: $L=\alpha_{NP}^2$ (ex: SM $L=\alpha_W^2$, SUSY $\alpha_{W,s}^2$)
- F flavour factor: depends on flavour structure of NP model

FLAVOUR STRUCTURES OF NP

- $\mathcal{L}^{SM}{}_{gauge}$ invariant under flavour $SU(3)^5$
  - MFV: broken only by V_{CKM} and m_t
    - same correlations as in the SM

      Gabrielli, Giudice, NPB433; Buras et al., PLB500; D'Ambrosio et al., NPB 645
  - MFV @ large tanβ: only V_{CKM} and m_t, m_b
    - lose correlations between K and B
    - scalar currents enhanced

      D'Ambrosio et al., NPB 645; Babu, Kolda; Isidori, Retico; Buras et al.; ...
  - NMFV: $V^U{}_{L,R}$, $V^D{}_{L,R}$ ~ V_{CKM} and m_t (m_b)

    Agashe et al
    - additional sources of FV, different chiralities

On the NP scale again:

$$\Lambda = \sqrt{\frac{F_i L_i}{C_i(\Lambda)}}$$

- Minimal Flavour Violation:
  - small tanβ: $F_1 = F_{SM} \sim (V_{tq} V_{tq'}^*)^2$ and $F_{i\neq 1} = 0$
  - large tanβ: additional operators in B_s mixing
- Next-to-Minimal Flavour Violation:
  - $|F_i| \sim F_{SM}$ with arbitrary phases
- Generic flavour structure
  - $|F_i| \sim 1$ with arbitrary phases

Generic Flavour Violation

UTfit collaboration, in preparation

PRELIMINARY

From ε_K:

$\Lambda > 2\ 10^5$ TeV (tree-level), $\Lambda > 7\ 10^3$ TeV (weak loop)

From Δm_K:

$\Lambda > 2\ 10^4$ TeV (tree-level), $\Lambda > 600$ TeV (weak loop)

From D mixing:

$\Lambda > 4\ 10^3$ TeV (tree-level), $\Lambda > 150$ TeV (weak loop)

From B_d mixing:

$\Lambda > 2\ 10^3$ TeV (tree-level), $\Lambda > 75$ TeV (weak loop)

From B_s mixing:

$\Lambda > 220$ TeV (tree-level), $\Lambda > 7$ TeV (weak loop)

Next-to-Minimal Flavour Violation

From ε_K: ***PRELIMINARY***

$\Lambda > 60$ TeV (tree-level), $\Lambda > 2$ TeV (weak loop)

From Δm_K:

$\Lambda > 4$ TeV (tree-level), $\Lambda > 130$ GeV (weak loop)

From B_d mixing:

$\Lambda > 14$ TeV (tree-level), $\Lambda > 460$ GeV (weak loop)

From B_s mixing:

$\Lambda > 8$ TeV (tree-level), $\Lambda > 260$ GeV (weak loop)

Clearly beyond the reach of the LHC for tree-level (warped extra-dim, etc.). Even weakly interacting loop-mediated on the border!!!

Minimal Flavour Violation

A worst-case scenario for NP searches...

For small tan β:

$\Lambda > 5.5$ TeV (tree-level)

$\Lambda > 185$ GeV (weak loop)

For large tan β (from D=6 operators):

$\Lambda > 5.1$ TeV (tree-level)

$\Lambda > 170$ GeV (weak loop)

Still well within the reach of LHC if weak loop...

Plus interesting phenomenology of Higgs effects

TOP-DOWN APPROACH: $\Delta F=1$ PROCESSES

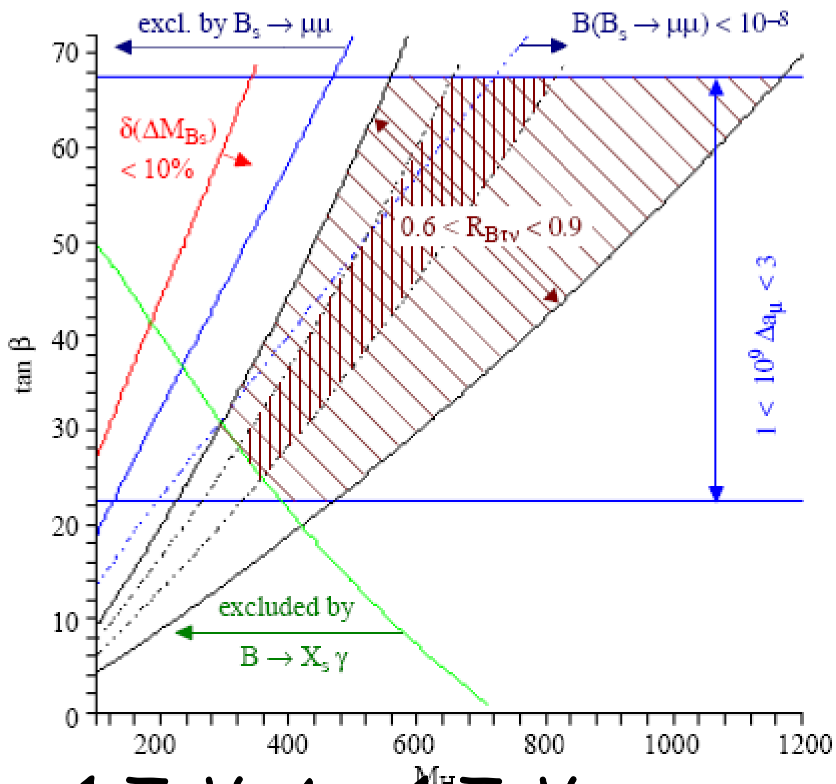
- Model-independent analyses of $\Delta F=1$ processes difficult: too many operators
- In specific models, apply $\Delta F=2$ constraints and study possible signals in $\Delta F=1$:
  - MFV models
  - SUSY models (with or without MFV)
  - Non-SUSY models (extra dim, little Higgs)

THE MSSM

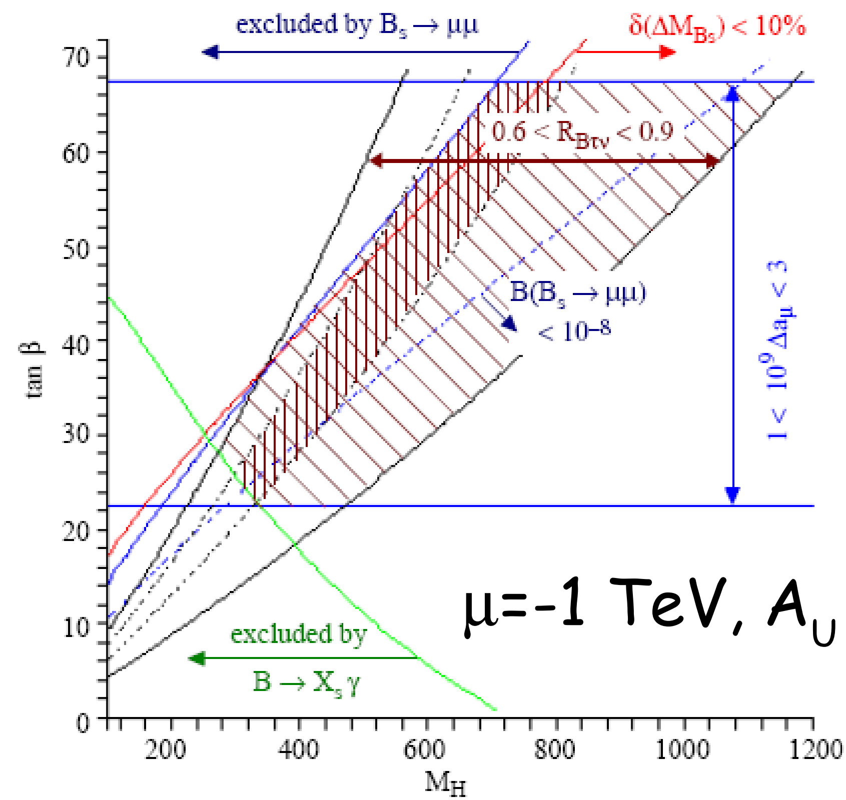
- In the MSSM, two classes of contributions to FCNC's:
  - Supersymmetrization of SM contributions ($W \to \tilde{w}$, $t \to \tilde{t}$) + $H^{\pm}$: also present in MFV
  - pure SUSY contributions: $\tilde{g}$ – $\tilde{q}$: requires new sources of flavour violation in squark mass matrices

Hall, Kostelecky & Raby; Gabbiani et al.

THE MFV-MSSM @ LARGE tanβ



μ=-1 TeV, A_U =1 TeV



μ=-1 TeV, A_U =2 TeV

Isidori & Paradisi 06

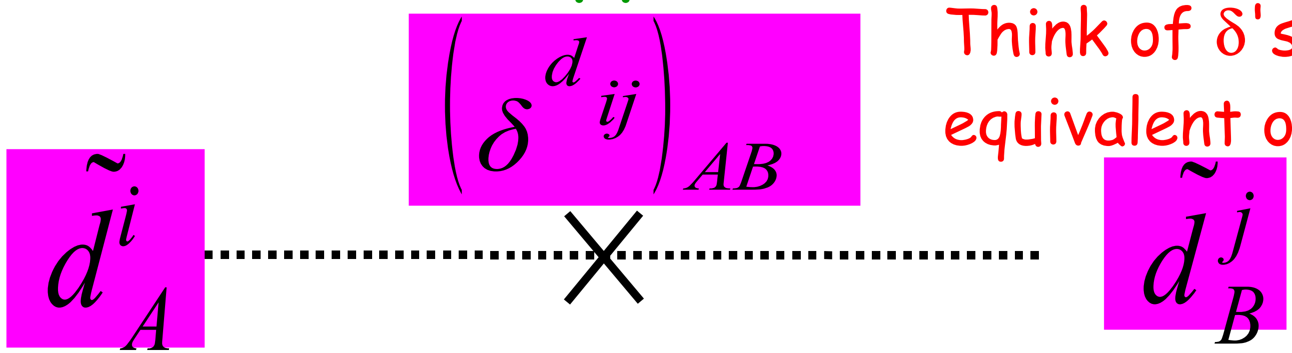
Violations of lepton universality possible if sizable LFV

THE GENERAL MSSM

Ciuchini et al., in progress, Preliminary

- We consider a MSSM with generic soft SUSY-breaking terms, but
  - dominant gluino contributions only
  - mass insertion approximation

Think of δ's as SUSY equivalent of CKM mixing



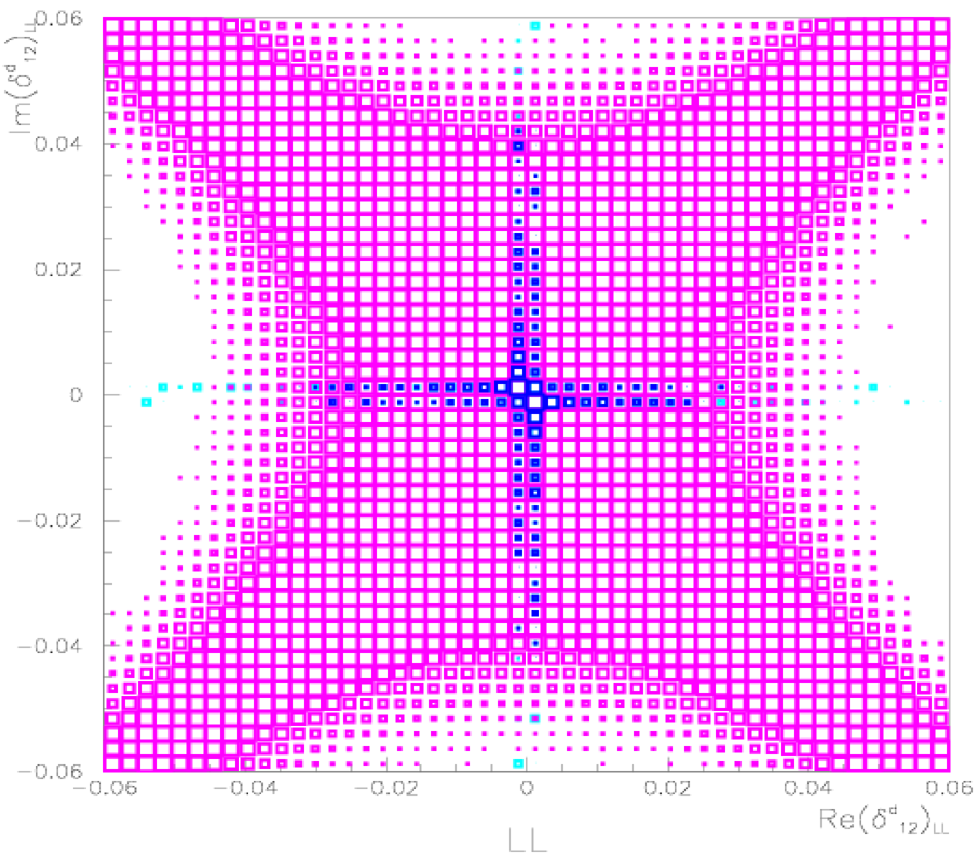
four insertions AB=LL, LR, RL, RR

CONSTRAINTS ON δ's

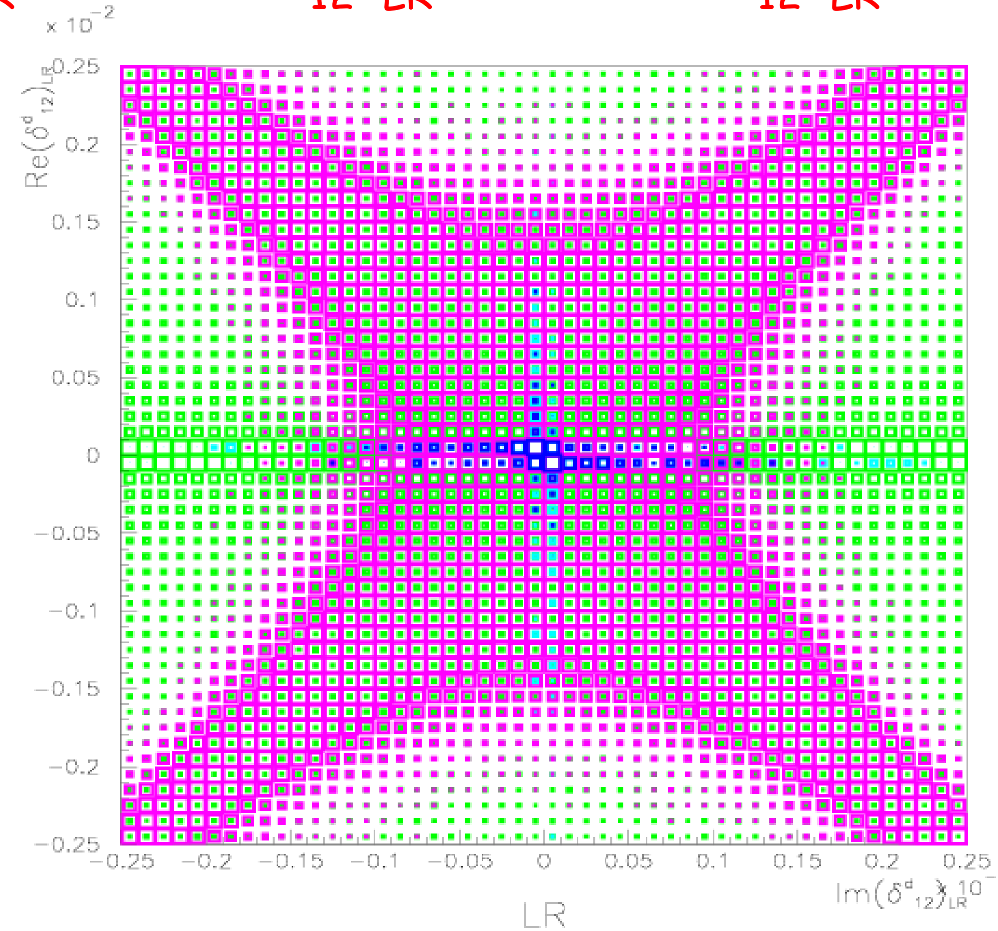
- $\left(\delta^{d}{}_{12}\right)_{AB}$ contribute to Kaon mixing: constraints from Δm_K & ε_K
- $\left(\delta^{d}{}_{13}\right)_{AB}$ contribute to B mixing: constraints from Δm_B & $\sin 2\beta$
- $\left(\delta^{d}{}_{23}\right)_{AB}$ contribute to Bs mixing and $b \to s$ decays:

  constraints from Δm_{Bs}, $b \to s\gamma$, $b \to s l^+ l^-$
- for reference, choose $m_{gl}=m_{sq}=350$ GeV

Re $(\delta^d_{12})_{LL,RR}$ vs Im $(\delta^d_{12})_{LL,RR}$



Re $(\delta^d_{12})_{LR}$ vs Im $(\delta^d_{12})_{LR}$



Δm_K only

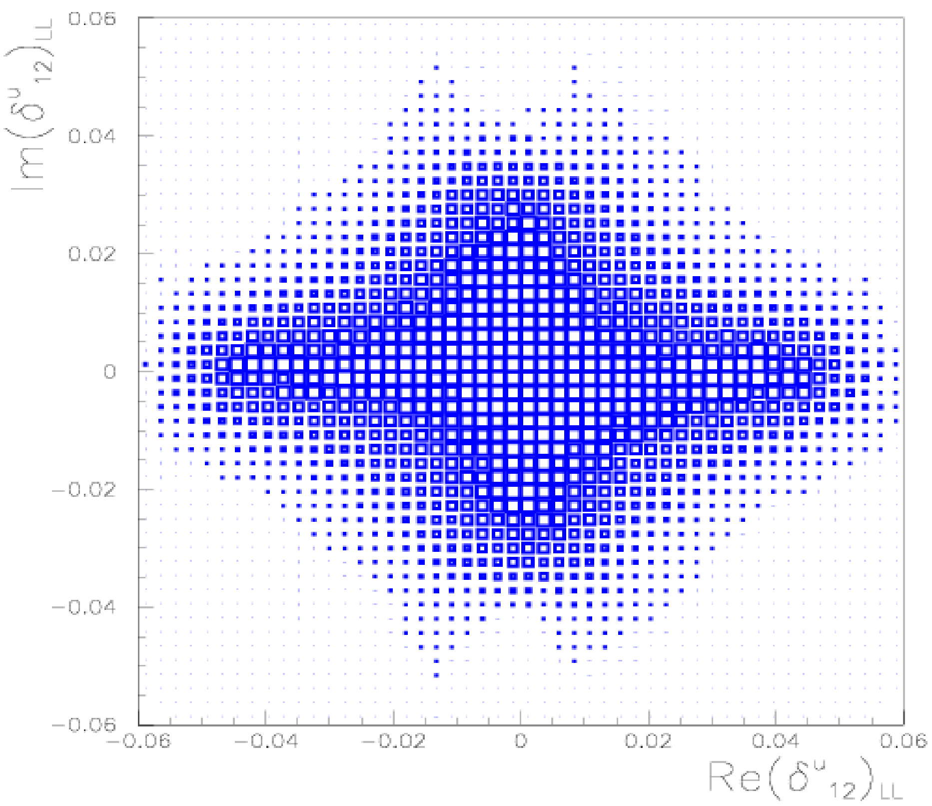
ε'/ε only

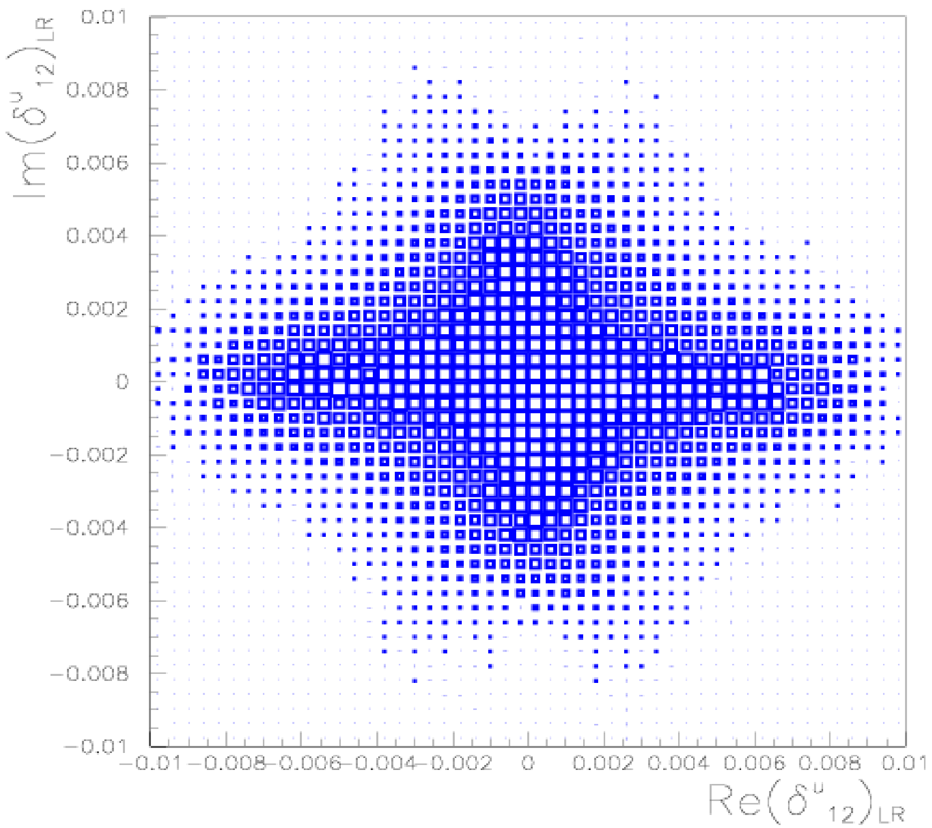
ε_K only

Δm_K and ε_K

$m_{sq}=m_{gl}=350$ GeV

$Re\,(\delta^u_{12})_{LL,RR}$ vs $Im\,(\delta^u_{12})_{LL,RR}$ $\quad$ $Re\,(\delta^u_{12})_{LR}$ vs $Im\,(\delta^u_{12})_{LR}$

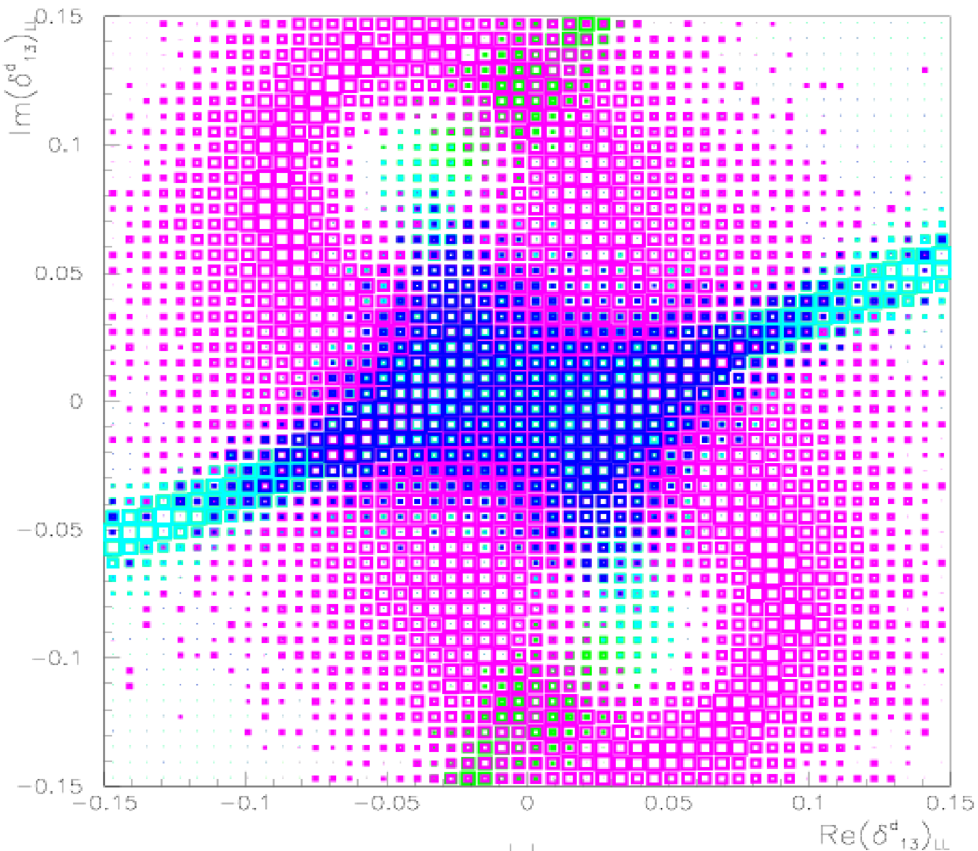


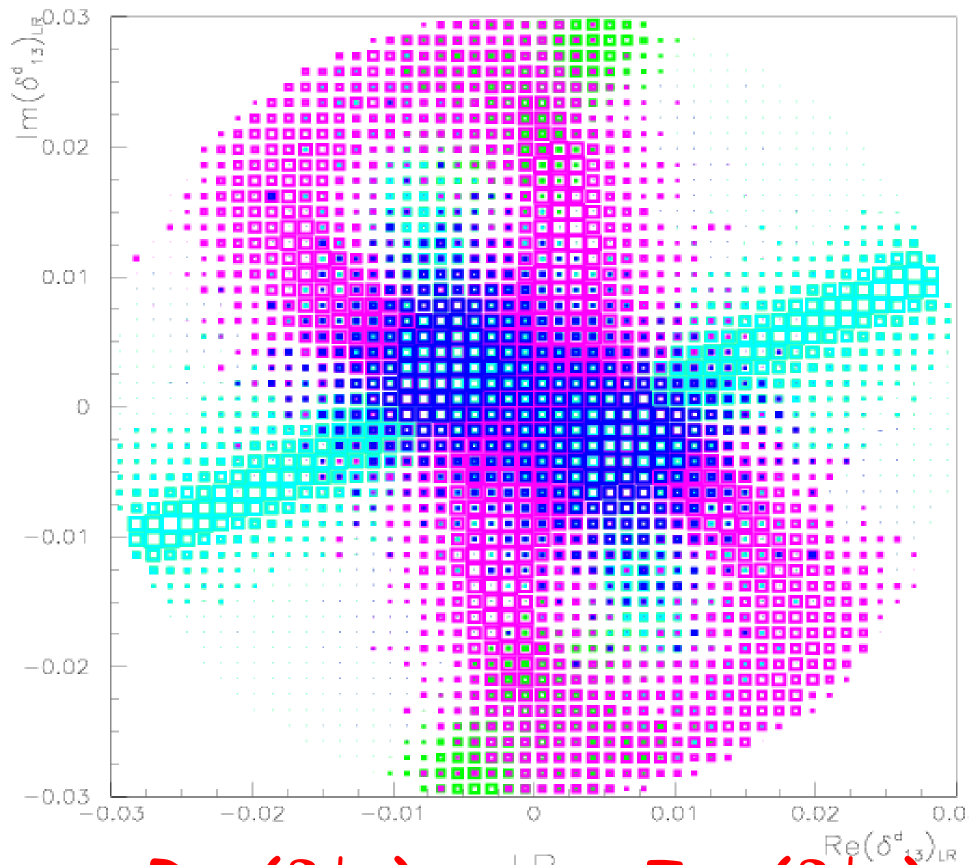


All information from D mixing combined

$m_{sq}=m_{gl}=350$ GeV

Ciuchini et al. '07





Re $(\delta^d_{13})_{LL,RR}$ vs Im $(\delta^d_{13})_{LL,RR}$

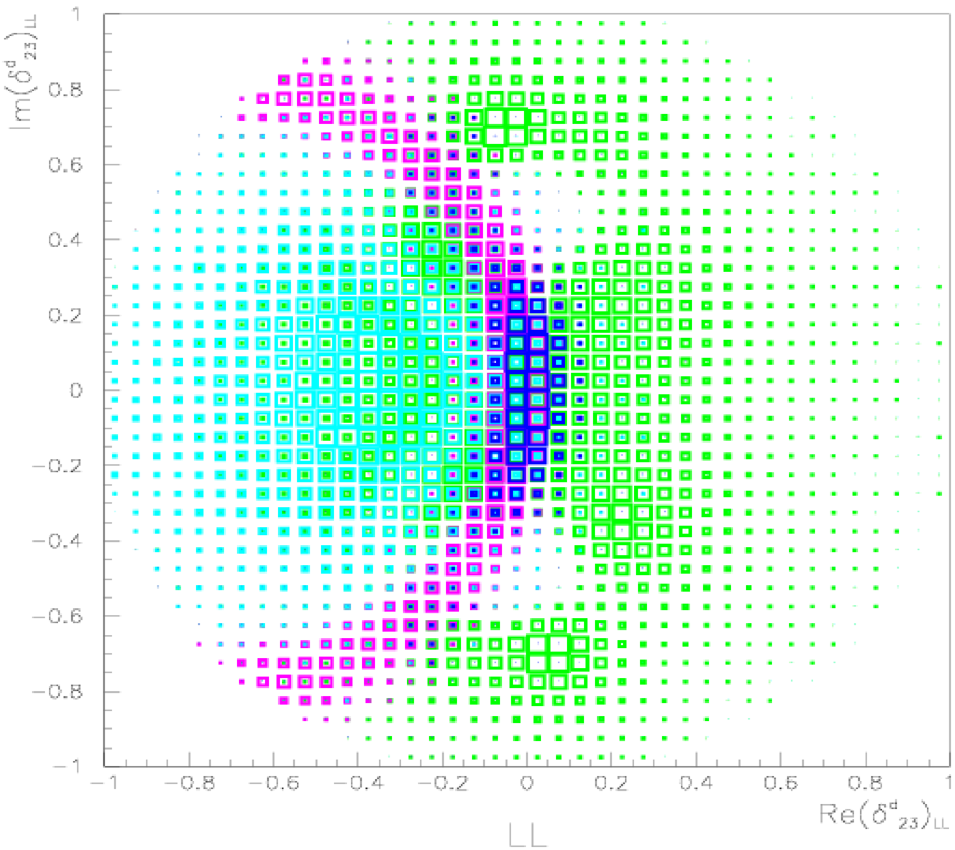
Re $(\delta^d_{13})_{LR,RL}$ vs Im $(\delta^d_{13})_{LR,RL}$

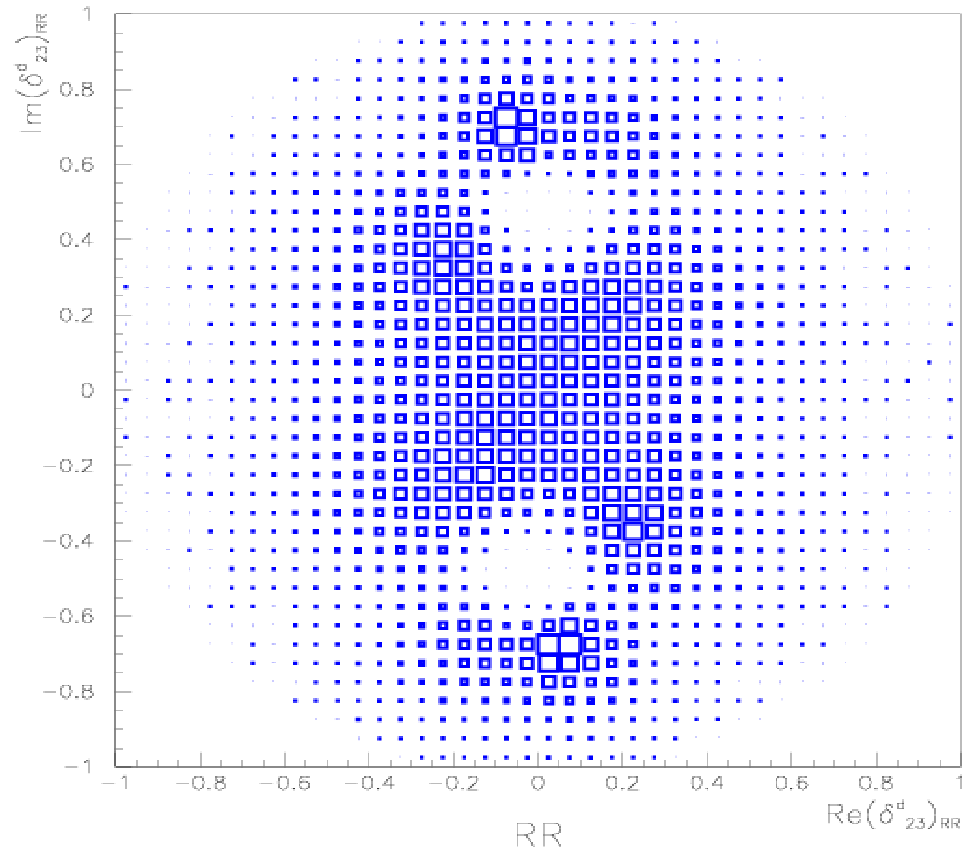
Δm_B only

sin 2β only

sin 2β and cos 2β

All constraints





Re $(\delta^d_{23})_{LL}$ vs Im $(\delta^d_{23})_{LL}$

$\tan\beta=3$

Constraint from $b \to s\, ll$

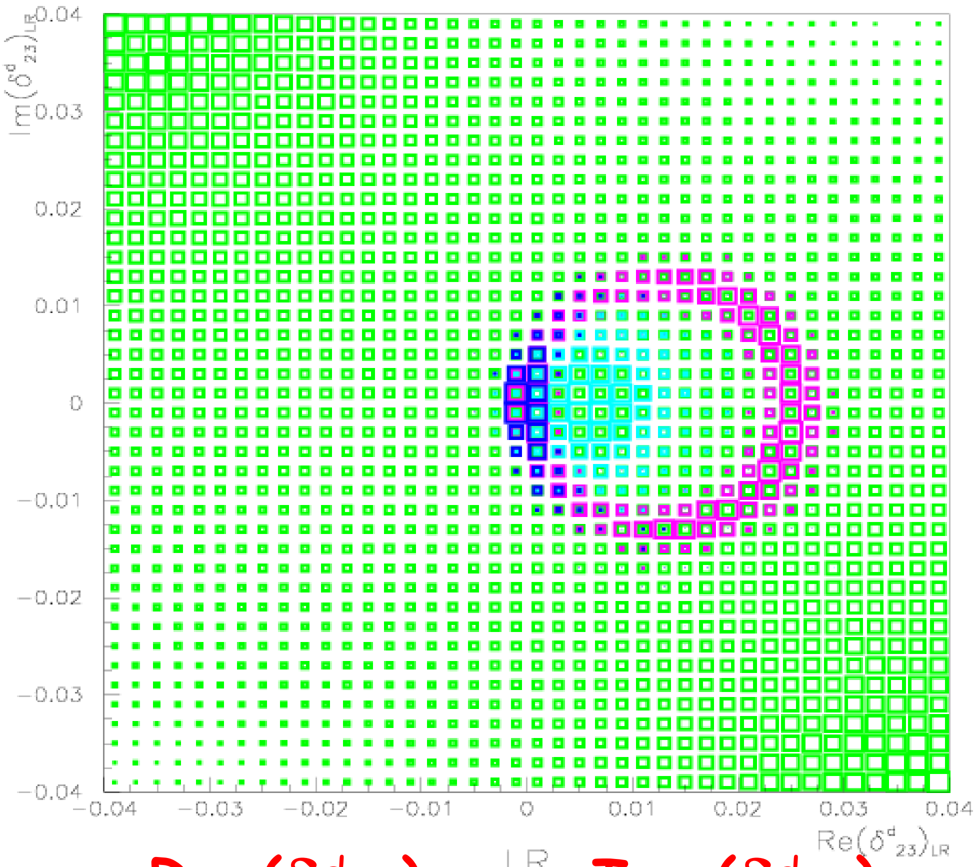
Constraint from $b \to s\, \gamma$

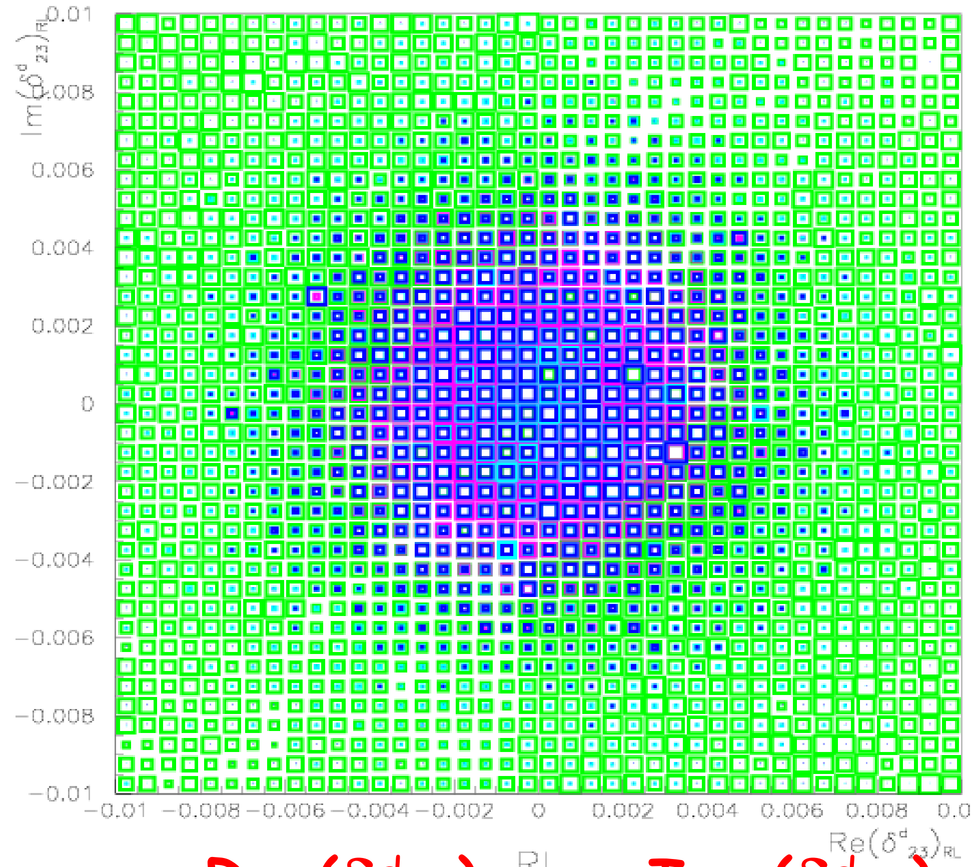
Constraint from C_{Bs}, ϕ_{Bs}

All constraints

Re $(\delta^d_{23})_{RR}$ vs Im $(\delta^d_{23})_{RR}$

RR case dominated by B_s mixing





Re $(\delta^d_{23})_{LR}$ vs Im $(\delta^d_{23})_{LR}$ Re $(\delta^d_{23})_{RL}$ vs Im $(\delta^d_{23})_{RL}$

LR & RL dominated by BR($b \to s\,\gamma$) & BR($b \to s\, l^+ l^-$)

RL does not interfere with the SM

$\left|\left(\delta^d_{12}\right)_{LL,RR}\right|$	$\left|\left(\delta^d_{12}\right)_{LL=RR}\right|$	$\left|\left(\delta^d_{12}\right)_{LR}\right|$	$\left|\left(\delta^d_{12}\right)_{RL}\right|$
$1 \cdot 10^{-2}$	$2 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$

$\left|\left(\delta^u_{12}\right)_{LL,RR}\right|$	$\left|\left(\delta^u_{12}\right)_{LL=RR}\right|$	$\left|\left(\delta^u_{12}\right)_{LR}\right|$	$\left|\left(\delta^u_{12}\right)_{RL}\right|$
$4 \cdot 10^{-2}$	$2 \cdot 10^{-3}$	$6 \cdot 10^{-3}$	$6 \cdot 10^{-3}$

$\left|\left(\delta^d_{13}\right)_{LL,RR}\right|$	$\left|\left(\delta^d_{13}\right)_{LL=RR}\right|$	$\left|\left(\delta^d_{13}\right)_{LR}\right|$	$\left|\left(\delta^d_{13}\right)_{RL}\right|$
$7 \cdot 10^{-2}$	$5 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$1 \cdot 10^{-2}$

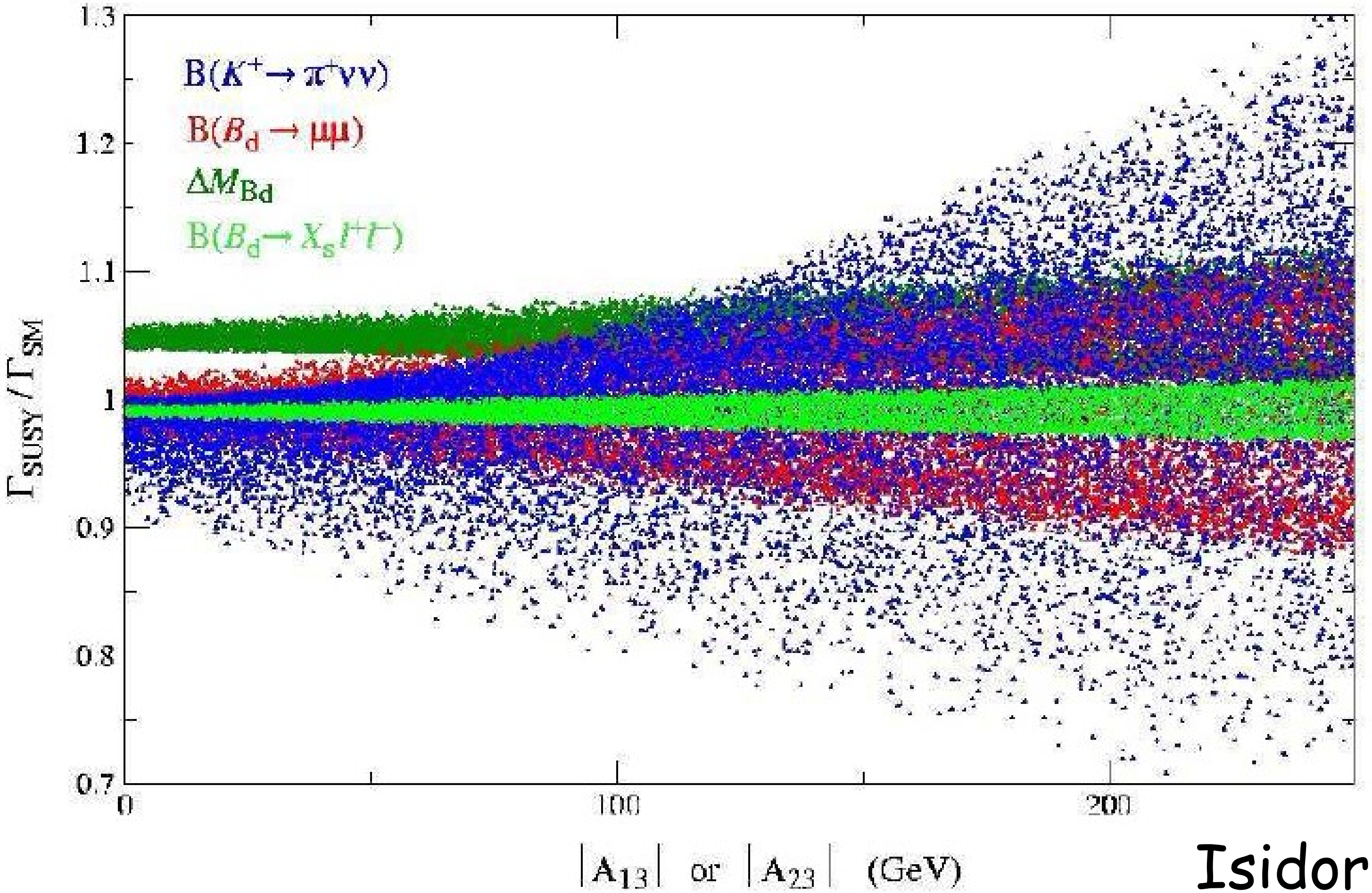
$\left|\left(\delta^d_{23}\right)_{LL}\right|$	$\left|\left(\delta^d_{23}\right)_{RR}\right|$	$\left|\left(\delta^d_{23}\right)_{LL=RR}\right|$	$\left|\left(\delta^d_{23}\right)_{LR,RL}\right|$
$2 \cdot 10^{-1}$	$7 \cdot 10^{-1}$	$5 \cdot 10^{-2}$	$5 \cdot 10^{-3}$

$m_{sq}=m_{gl}=-\mu=350$ GeV, $\tan\beta = 3$;

all bounds scale approx. as $m_{SUSY}/350$ GeV

EFFECTS OF LR UP-TYPE δ's

Colangelo & Isidori

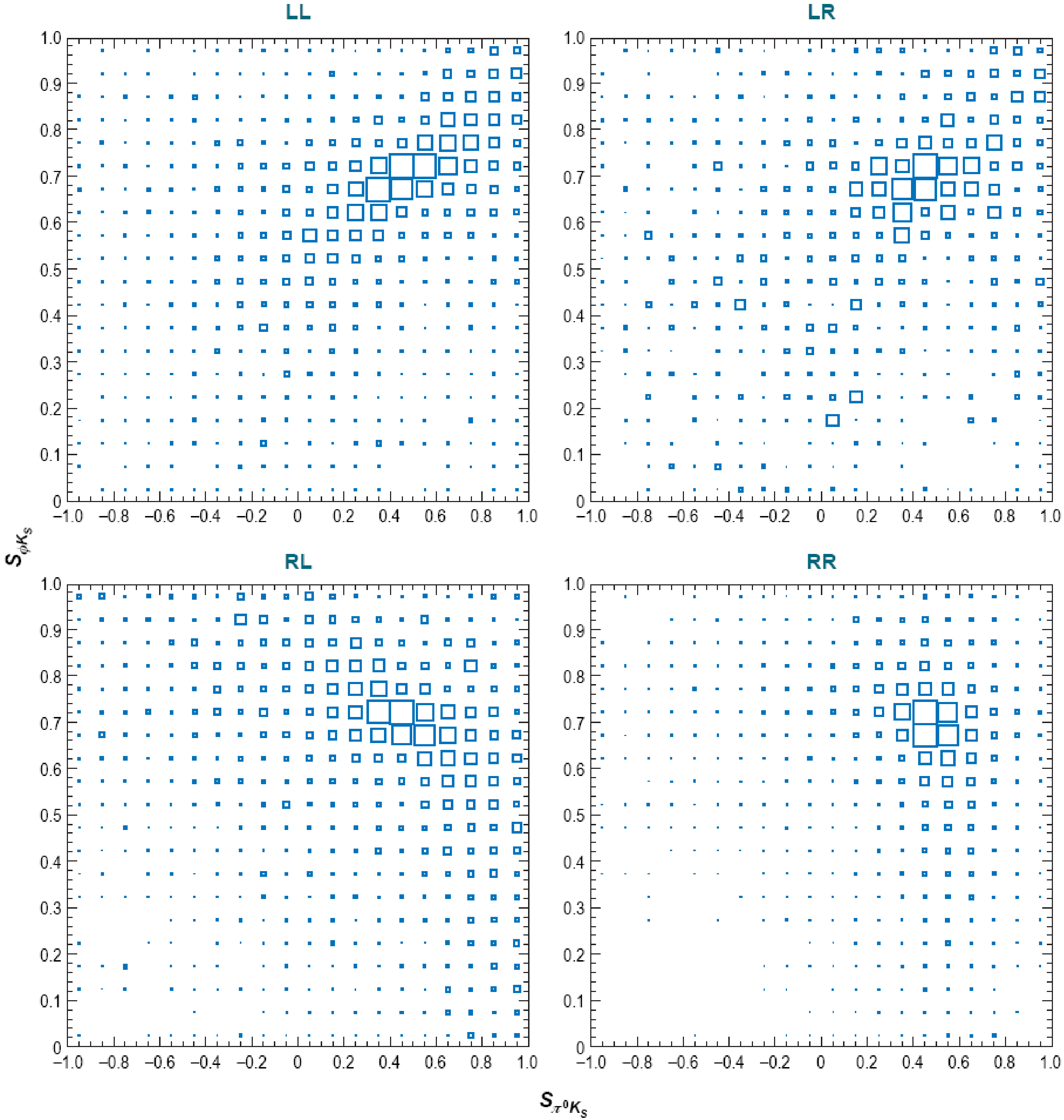


Isidori et al 06

EFFECTS OF (δ^d_{23})

Bertolini, Borzumati, Masiero, NPB294; Ciuchini et al., PRL79; Barbieri, Strumia, NPB508; Kagan, Neubert, PRD58; Abel, Cottingham, Wittingham PRD58; Borzumati et al., PRD62; Besmer, Greub, Hurth NPB609; Lunghi, Wyler, PLB521; Causse; Hiller, PRD66; Khalil, Kou PRD67; Kane et al., PRL90; Harnik et al.; Ciuchini et al., PRD67; Baek, PRD67; Hisano, Shimizu, PLB581; Gabrielli et al., NPB710; Khalil, hep-ph/0505151;…

- Large values of (δ^d_{23}) well motivated: SUSY flavour models, SUSY-GUTs and neutrino oscillations
- Possible hints of NP in time-dependent CP viol. in $b \to s$ penguins ($B \to \phi K_s$, $B \to \pi K_s$)



Ciuchini et al

CONCLUSIONS - I

- Flavour physics is a powerful probe of NP
- B-factories + TeVatron: from O(1) to O(10%) NP effects in all sectors (except ϕ_{Bs}); 2015 goal: O(1%) in all sectors (LHCb, SFF, lattice QCD, JPARC)
- Bottom-up approach for $\Delta F=2$: operator analysis gives strong constraints on the scale of NP

CONCLUSIONS - II

- Sensitivity to scales much higher than m_{EW}:
  - NP models with generic flavour structure far beyond LHC
  - NP models with NMFV:
    - beyond the reach of LHC if tree-level FCNC
    - at the border of LHC if loop-mediated, weakly int.
  - MFV models still within LHC reach
    - top-down approach to test model-dependent predictions and correlations

CONCLUSIONS - III

- Different classes of SUSY models can be discriminated:
  - SUSY MFV @ low tanβ: O(<10%) effects in UTA, rare K and B decays
  - SUSY MFV or heavy squarks @ large tanβ: large effects in $B_s \to \mu\mu$ & $B \to \tau\nu$
  - SUSY with FV confined to 3rd generation
    - nonuniversal A_t: rare K decays
    - δ_{23}: $b \to s$ penguins

GENERAL CONSIDERATIONS

- Pattern of NP effects depends on operators generated at the hadronic scale

	$s\to d$	$b\to d$	$b\to s$
EWP	$K\to\pi\nu\nu$	$b\to dll$	$b\to sll$
	$K\to\pi ee$	$B\to\pi\pi,\ldots$	$B\to K\pi,\ldots$
	$K\to\mu\mu$	$b\to d\nu\nu$	$b\to s\nu\nu$
	ε'		
magnetic	$K\to\pi ee$	$b\to d\gamma$	$b\to s\gamma$
	ε'	$b\to dll$	$b\to sll$
		$B\to\pi\pi,\ldots$	$B\to K\pi,\ldots$
scalar		$b\to dll$	$b\to sll$
		$B\to\mu\mu,\ldots$	$B_s\to\mu\mu,\ldots$
		$B\to\tau\nu,\ldots$	Δm_s

MFV @ SMALL tanβ (CMFV)

Improved Bounds (2007)

Including Impact from R_b^0, A_b, $A_{FB}^{0,b}$

The sign of Z-penguin Amplitude in CMFV is SM like

Haisch Weiler (2007)

Branching Ratios	CMFV (95%)	SM (95%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	3.9-10.7	5.5-9.5	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	1.2-4.5	2.3-3.6	$<2.1 \cdot 10^4$
$Br(B \to X_s \nu\bar{\nu}) \cdot 10^5$	1.5-4.7	3.0-3.6	<64
$Br(B_s \to \mu^+\mu^-) \cdot 10^9$	0.8-6.1	2.9-4.2	$<1.0 \cdot 10^2$
$Br(B_d \to \mu^+\mu^-) \cdot 10^{10}$	0.2-1.5	0.9-1.3	$<3.0 \cdot 10^2$

42 CERN0307 A. Buras