B physics and CP violation in the Standard Model and beyond

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- Introduction
- B physics and the Unitarity Triangle
- The Unitarity Triangle beyond the SM
- Minimal Flavour Violation
- Beyond MFV: general SUSY models
- Conclusions & Outlook

see www.utfit.org for details & updates

INTRODUCTION

- In the SM, Yukawa couplings are the only source of flavour and CP violation in weak processes. Everything can be written in terms of quark masses and the CKM matrix.
- No tree-level FCNC (GIM mechanism)

  ⇨ quantum corrections computable and sensitive to higher-dim operators ⇨ powerful probe of NP
- Flavour SU(3) strongly broken, 3rd generation has large coupling to EW breaking sector

  ⇨ expect NP effects to show up in B physics

4 QUESTIONS FOR THIS TALK

1) How good is our knowledge of the SM UT?

2) How severe are the constraints on NP from the UT analysis?

3) What have we learned on the structure of NP from B physics and the UT?

4) Can we expect to learn more in the near future?

THE UNITARITY TRIANGLE

Wolfenstein-Buras parameterization:

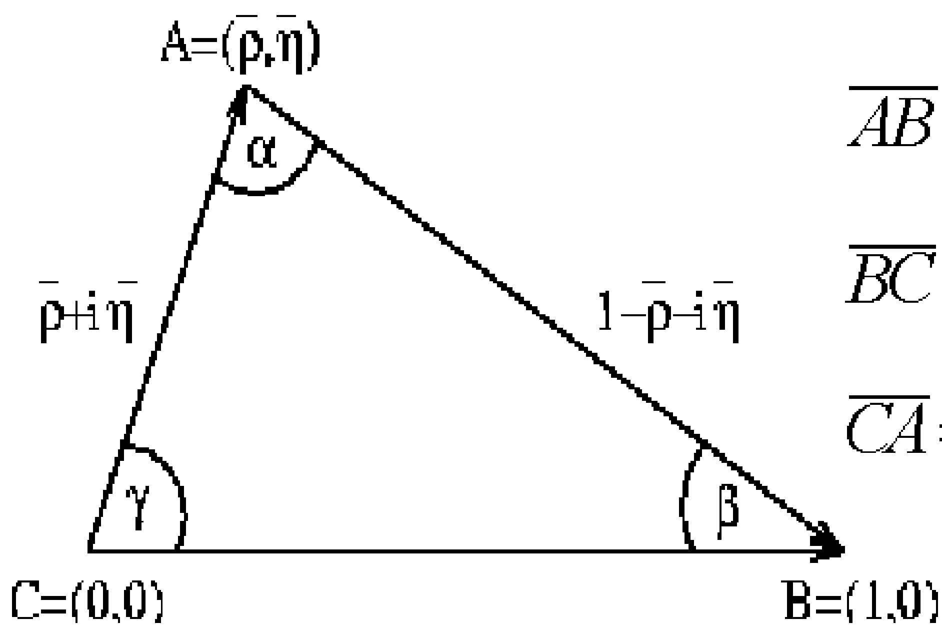
$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

A useful unitarity relation:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Defines a triangle in terms of $\bar{\rho}$ and $\bar{\eta}$:

The Unitarity Triangle



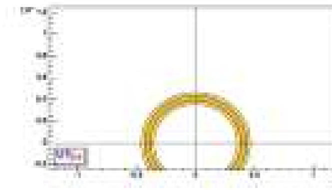
$$\overline{AB} = \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$$

$$\overline{BC} = 1$$

$$\overline{CA} = \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

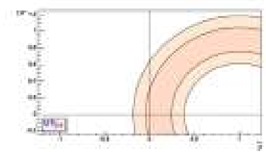
B physics summarized on the UT

Most of B physics measurements can be translated on the UT:

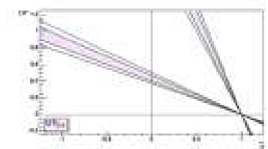


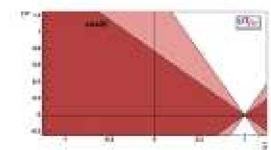
BR($b \to c l \nu$), BR($B \to D^{(*)} l \nu$) — $|V_{cb}|$

BR($b \to u l \nu$), BR($B \to \pi l \nu$) — $|V_{ub}|$



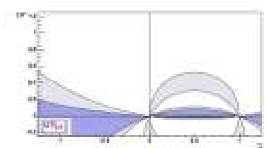
Δm_d (B_d-$\bar{B}_d$ mass diff.) — $|V_{td}^2|$



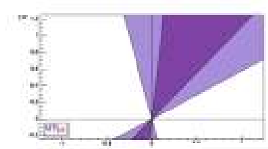


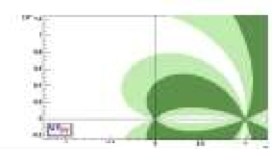
A_{CP}($b \to c\bar{c}s$) (J/ψ K, ...) — sin 2β, cos 2β

A_{CP}($b \to s\bar{s}s$, $d\bar{d}s$) (ϕ K, πK, ...) — sin 2β

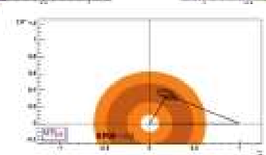


A_{CP}($b \to d\bar{d}d$, $u\bar{u}d$) ($\pi\pi$, $\rho\rho$, ...) — sin 2α

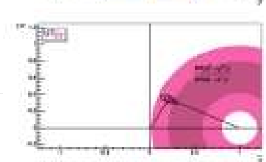




BR($b \to cud$, cus) (DK, ...) — γ, sin $(2\beta + \gamma)$



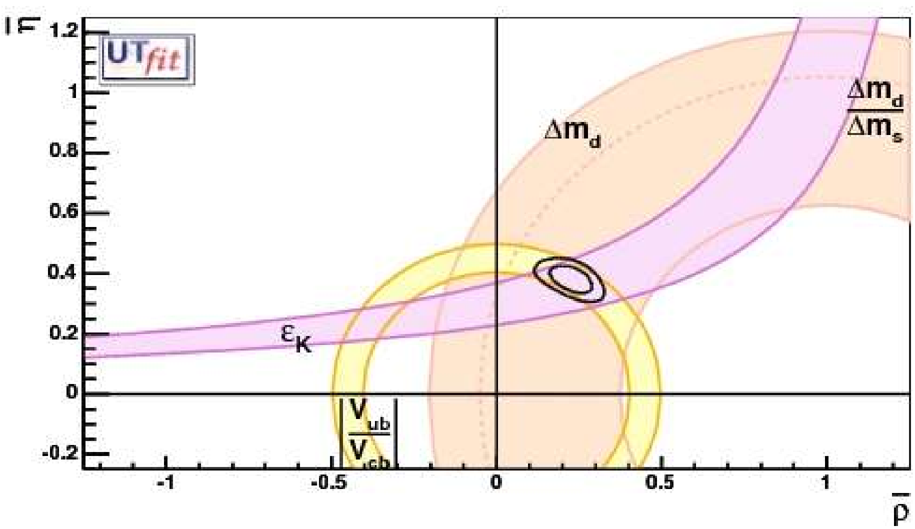
BR($B \to \tau\nu$) — $|V_{ub}|$

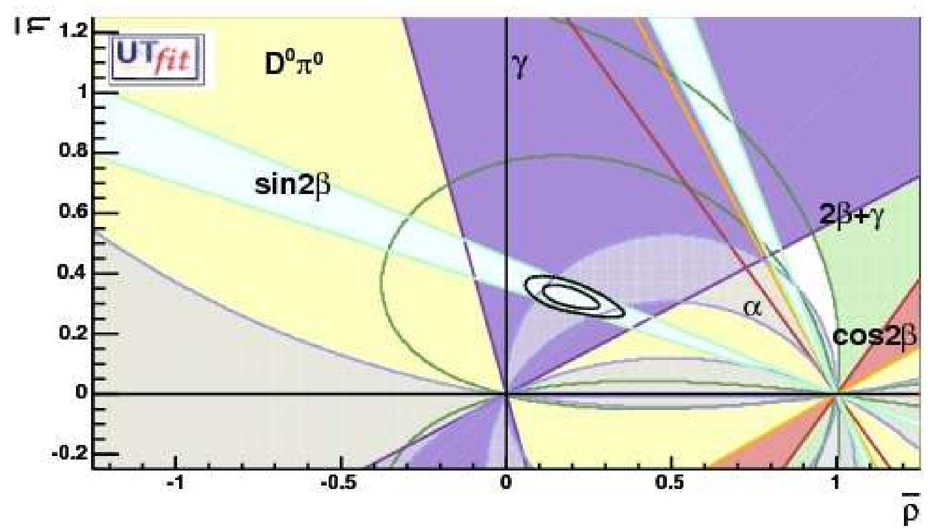


BR($B \to \rho\gamma$)/BR($B \to K^*\gamma$) — $|V_{td}|$

Progress of the UT analysis

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

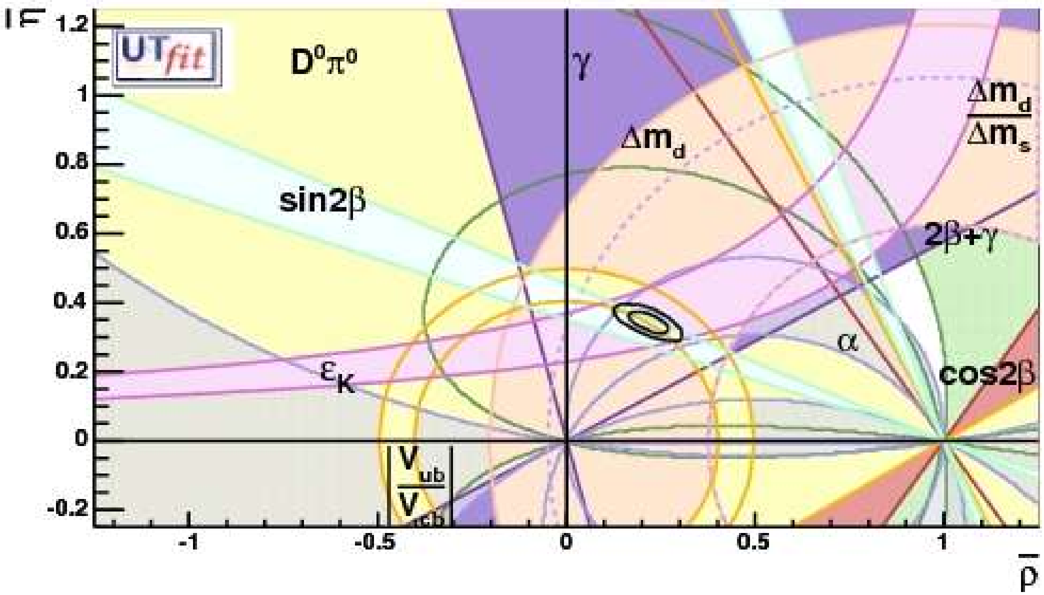




No angles:
$|V_{ub}/V_{cb}|$, Δm_d, ΔM_s, ε_K

Angles only: $\sin 2\beta$, $\cos 2\beta$, $\sin 2\alpha$, γ

ANSWER TO QUESTION 1) - THE SM UT

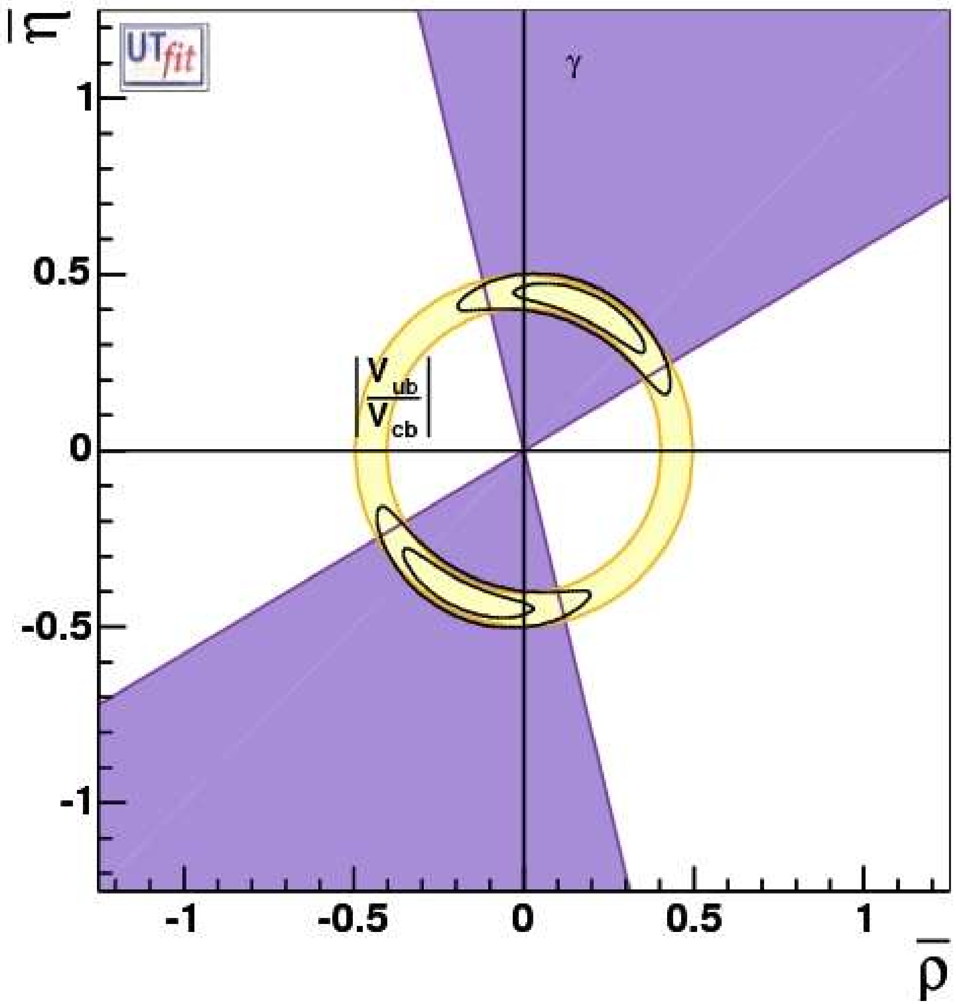


Slight disagreement between V_{ub} and $\sin 2\beta$ after summer conferences

Parameter	value	95% prob.
ρ	0.216 ± 0.036	[0.143,0.288]
η	0.342 ± 0.022	[0.300,0.385]
$\alpha(°)$	98.5 ± 5.7	[87.1,109.8]
$\beta(°)$	23.8 ± 1.5	[21.3,26.2]
$\gamma(°)$	57.6 ± 5.5	[46.8,68.7]
$\sin 2\alpha$	-0.29 ± 0.19	[-0.64,0.09]
$\sin 2\beta$	0.735 ± 0.024	[0.688,0.781]
$\sin(2\beta+\gamma)$	0.959 ± 0.028	[0.890,0.996]
$\Delta(ms)$ (ps^{-1})	20.0 ± 1.8	[15.5,24.2]

BEYOND THE SM I: THE REFERENCE UT

Assumptions:
(1) 3-generations unitarity
(2) no new physics in tree-level processes



$\bar{\rho} = \pm 0.18 \pm 0.12$

$\bar{\eta} = \pm 0.41 \pm 0.05$

$\sin 2\beta = 0.782 \pm 0.065$
-0.641 ± 0.087

$\gamma = (65 \pm 18)^\circ \cup (-115 \pm 18)^\circ$

$\alpha = (87 \pm 15)^\circ \cup (-46 \pm 15)^\circ$

Any model of new physics must satisfy these constraints

UTfit coll., hep-ph/0501199;
Botella et al., hep-ph/0502133

A more ambitious strategy:

1. Add most general NP to all sectors
2. Use all available info
3. Constrain simultaneously ρ, η and NP contributions

Botella et al., hep-ph/0502133;
Agashe et al., hep-ph/0509117;
UTfit coll., hep-ph/0509xxx.
Previous attempts:
Ciuchini et al., hep-ph/0307195;
CKMfitter group, hep-ph/0406184;
Ligeti, hep-ph/0408267.

Only possible thanks to the new measurements of CKM angles!!!
Will become the standard fit in the near future...

General parametrization of the mixing amplitudes

$B_q - \overline{B}_q$ mixing: $A_{B_q} = C_q e^{2i\phi_q} A_{B_q}^{\mathrm{SM}}$

$K - \overline{K}$ mixing: $\mathrm{Im}\, A_K = C_\varepsilon \, \mathrm{Im}\, A_K^{\mathrm{SM}}$

Soares, Wolfenstein PRD47;
Deshpande,Dutta, Oh PRL77;
Silva, Wolfenstein PRD55;
Cohen et al. PRL78;
Grossman, Nir, Worah PLB407;
Ciuchini et al. @ CKM Durham

$$(\Delta M_q) = C_q (\Delta M_q)^{SM}$$

$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}(J/\Psi K_S) = \sin 2(\beta + \phi_d)$$

$$\alpha^{exp} = \alpha - \phi_d$$

$$A_{\mathrm{SL}} \equiv \frac{\Gamma(\bar{B}^0 \to \ell^+ X) - \Gamma(B^0 \to \ell^- X)}{\Gamma(\bar{B}^0 \to \ell^+ X) + \Gamma(B^0 \to \ell^- X)}$$

$$A_{SL} = -\mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\sin 2\phi_d}{C_d} + \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\cos 2\phi_d}{C_d}$$

Laplace et al., PRD65

	ρ, η	C_d	ϕ_d	C_s	ϕ_s	C_ε	NP in $\Delta F=1$
γ	X						
$\|V_{ub}/V_{cb}\|$	X						
ΔM_d	X	X					
ΔM_s	(X)			X			
ε_K	X					X	
$A_{CP}(B \to J/\Psi K_s)$	X		X				
$A_{CP}(B \to J/\Psi K^*)$	X		X				
α ($\rho\rho$, $\rho\pi$, $\pi\pi$)	X		X				X
A_{SL}	X	X	X				X
$A_{CP}(B_s \to J/\Psi \Phi)$	(X)				X		

(3) assume NP in $b \to d$ decays is SU(2) invariant

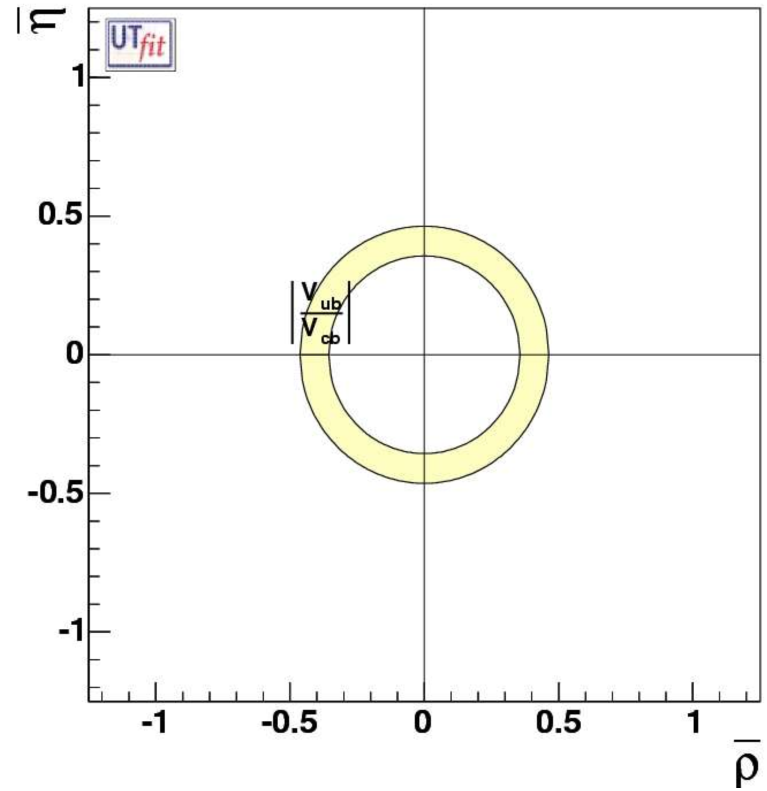
Use: $|V_{ub}/V_{cb}|$, γ, ΔM_d, ΔM_s, α, sin 2β, cos 2β and A_{SL}

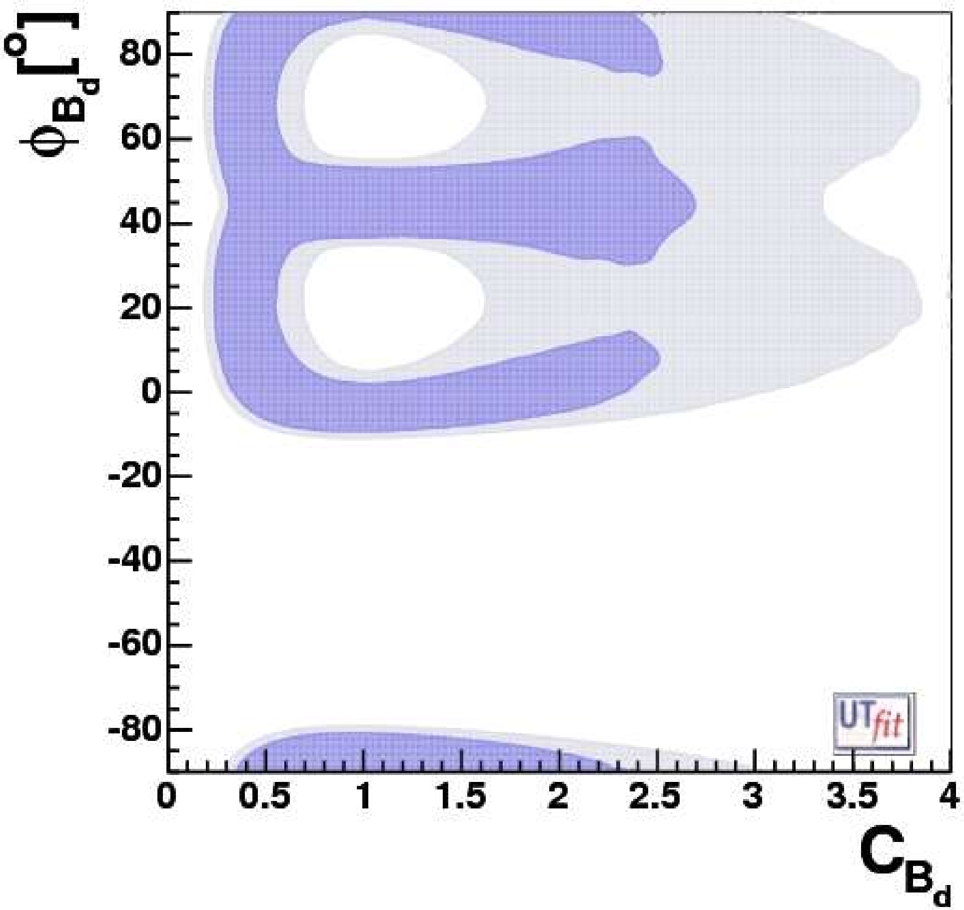
constrain simultaneously ρ, η, C_d, ϕ_d, C_s and C_ε

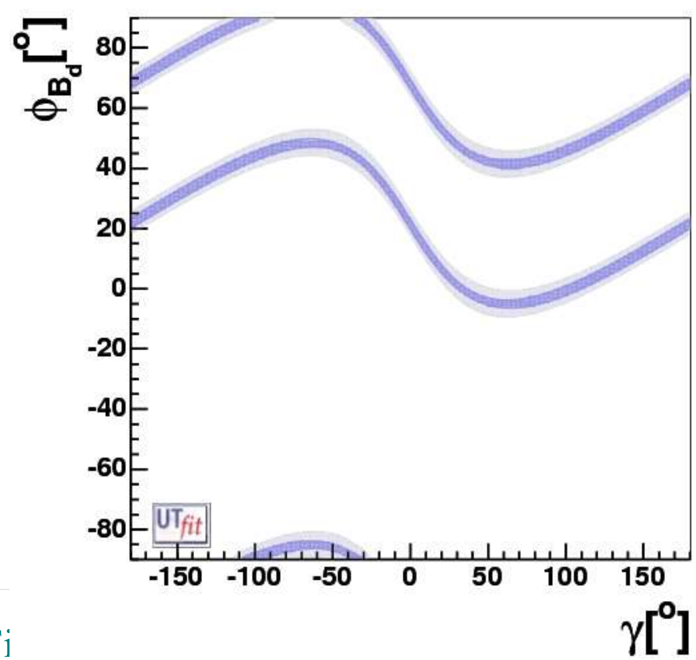
(no handle at present on ϕ_s - wait for LHCb)

Using:

- ε, Δm_d, $\sin 2\beta$

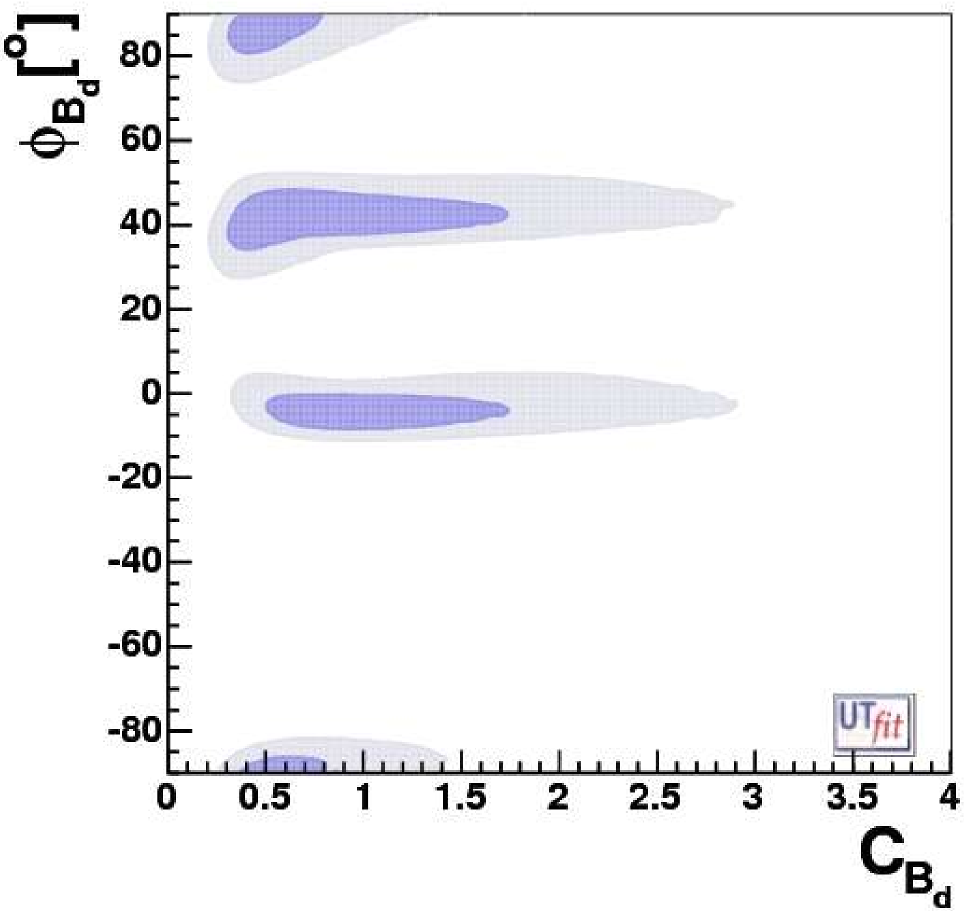


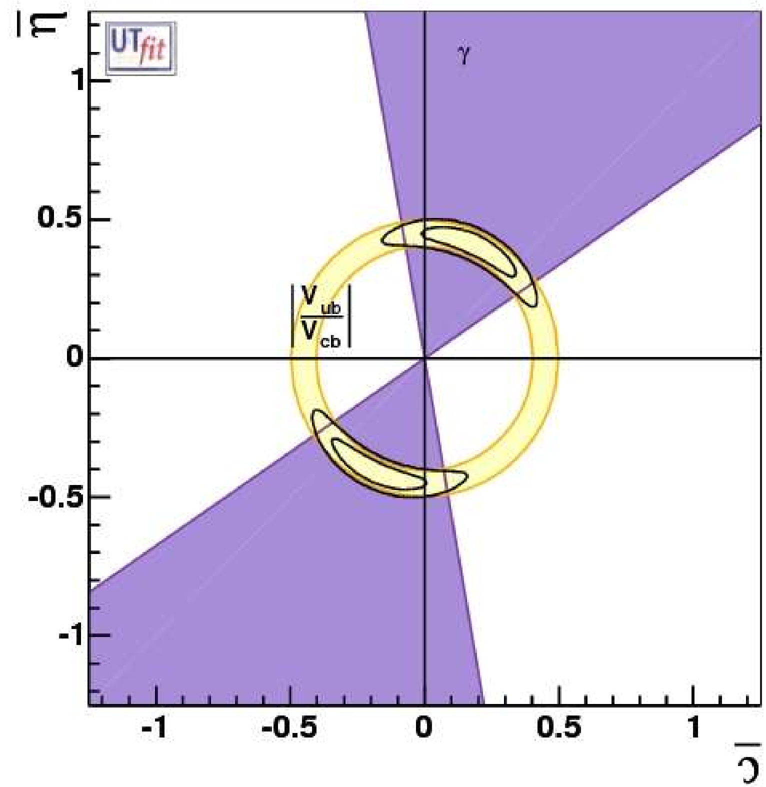


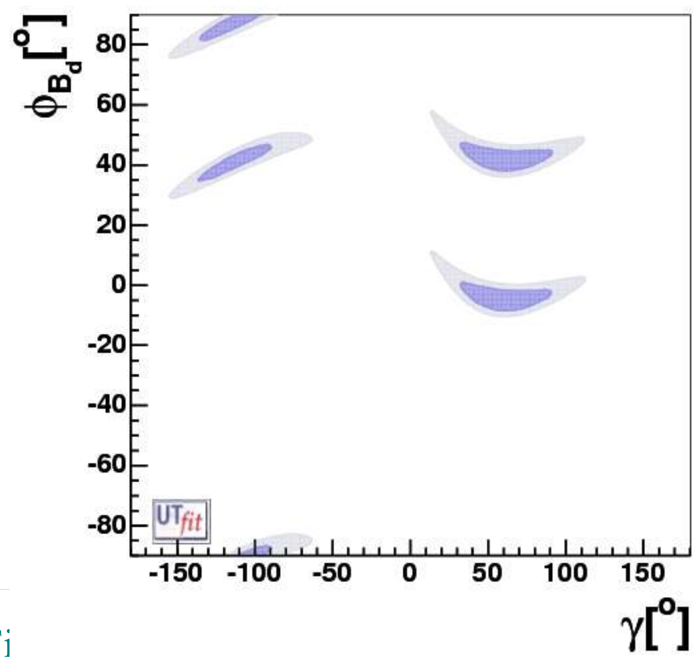


Using:

- ε, Δm_d, sin 2β
- γ







4 solutions for ρ, η, C_d and ϕ_d:

	γ	C_d	ϕ_d	$\cos 2(\beta+\phi_d)$	$\sin 2(\alpha-\phi_d)$	$\sin(2(\beta+\phi_d)+\gamma)$	A_{SL}
SM-LIKE	60°	1	0°	0,68	-0,23	0,96	OK
NP 1	60°	1	43°	-0,68	0,96	-0,23	OK
NP 2	120°	0,4	40°	0,68	-0,23	-0,96	$O(10^{-2})$
NP 3	120°	0,4	83°	-0,68	0,96	0,23	OK

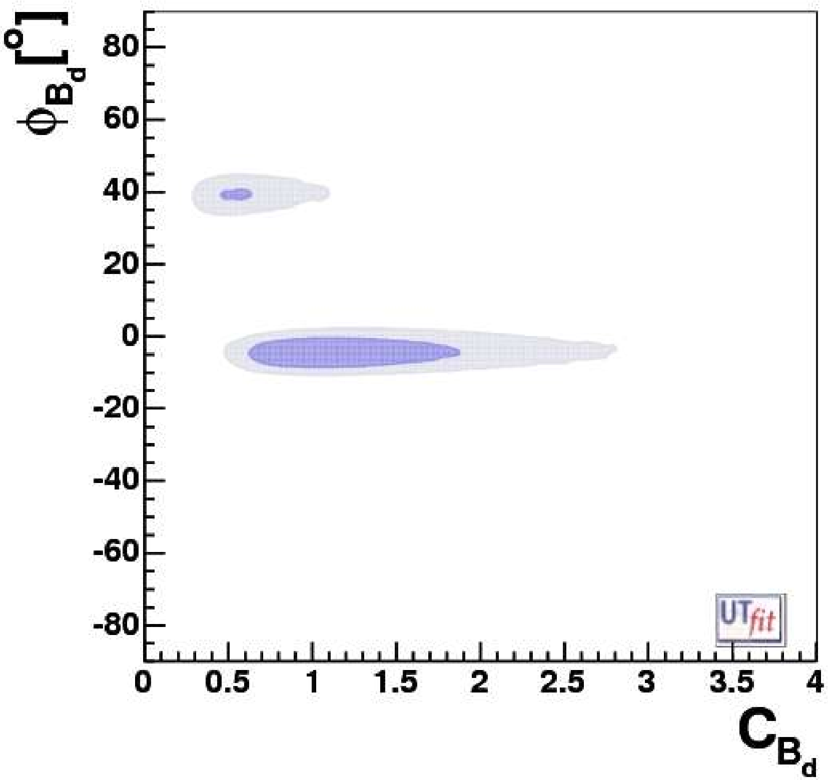
NP 1 & 3 solutions can be eliminated using angle measurements (α most effective at present)

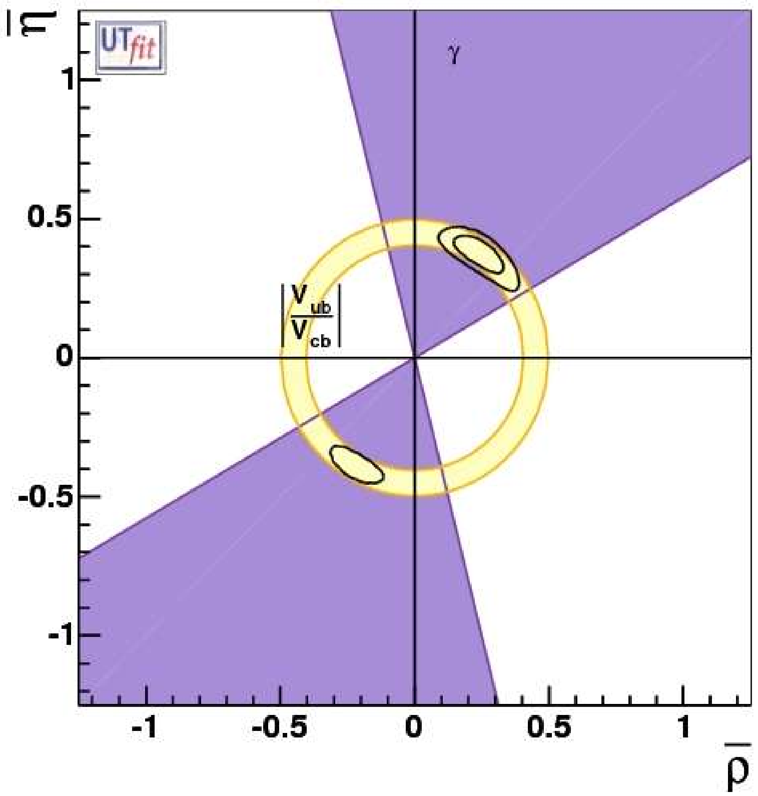
NP 2 solution can be suppressed using $A_{SL}=(-3\pm7)\ 10^{-3}$

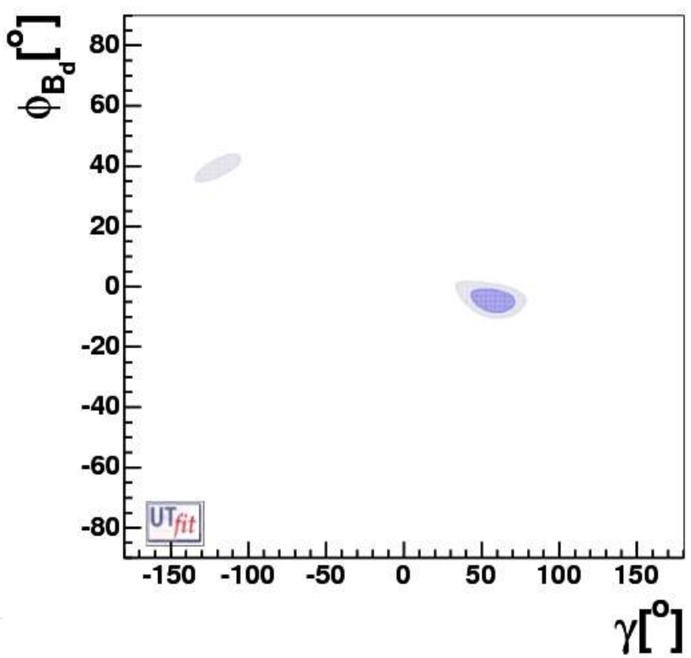
$\Rightarrow$ the SM-like solution is strongly favoured!

Using:

- ε, Δm_d, $\sin 2\beta$
- γ
- α, $\cos 2\beta$ & A_{SL}

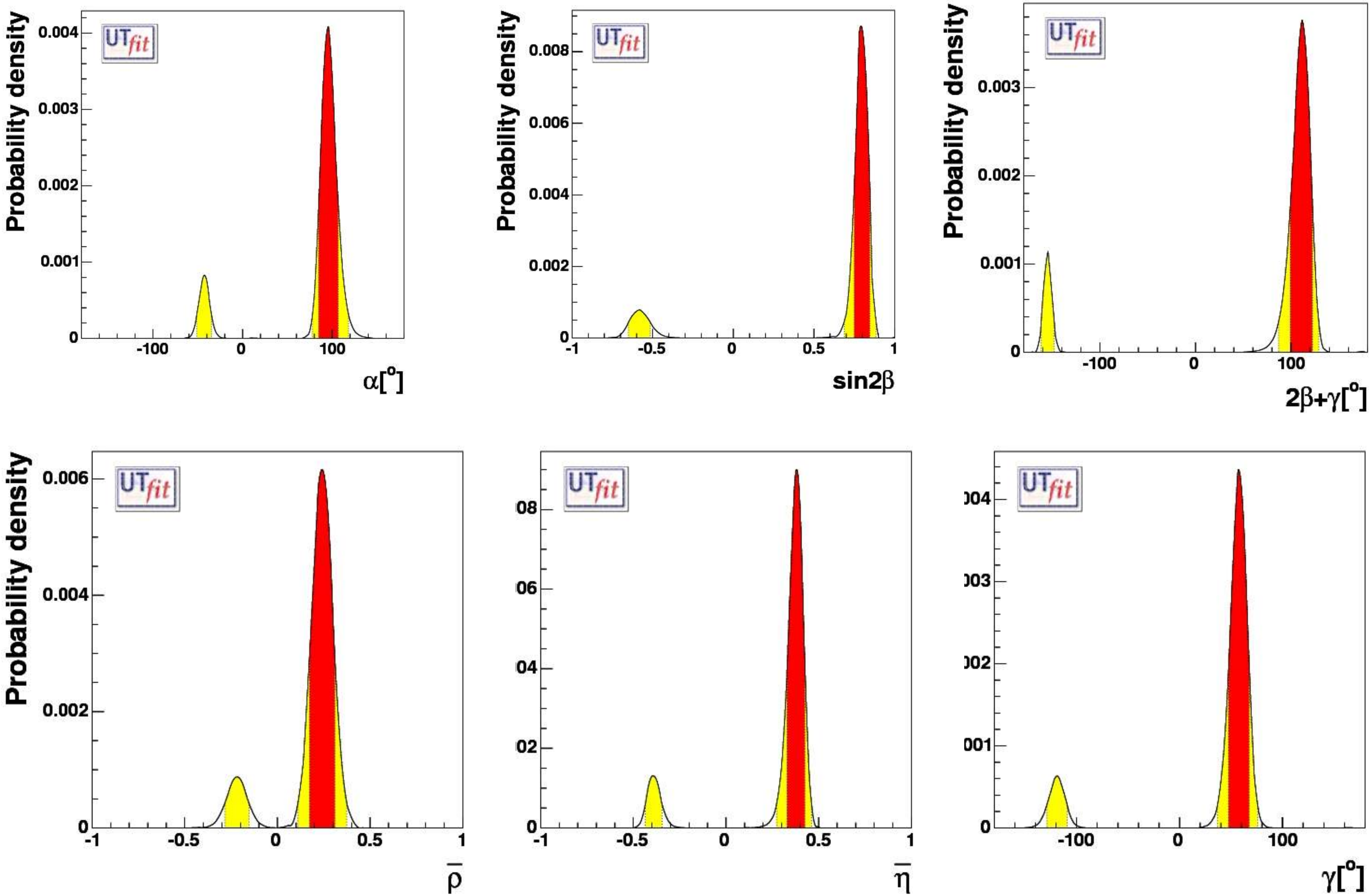






SM solution @ 88% prob.

NP solution @ 12% prob.

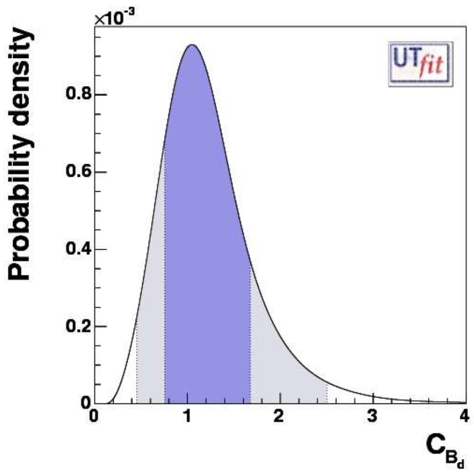

UTfit
Probability density
0.004
0.003
0.002
0.001
0
-100
0
100
α[°]
0.008
0.006
0.004
0.002
-1
-0.5
0.5
1
sin2β
2β+γ[°]
0.006
ρ̄
η̄
γ[°]

Question 2) - How large is the NP contribution?

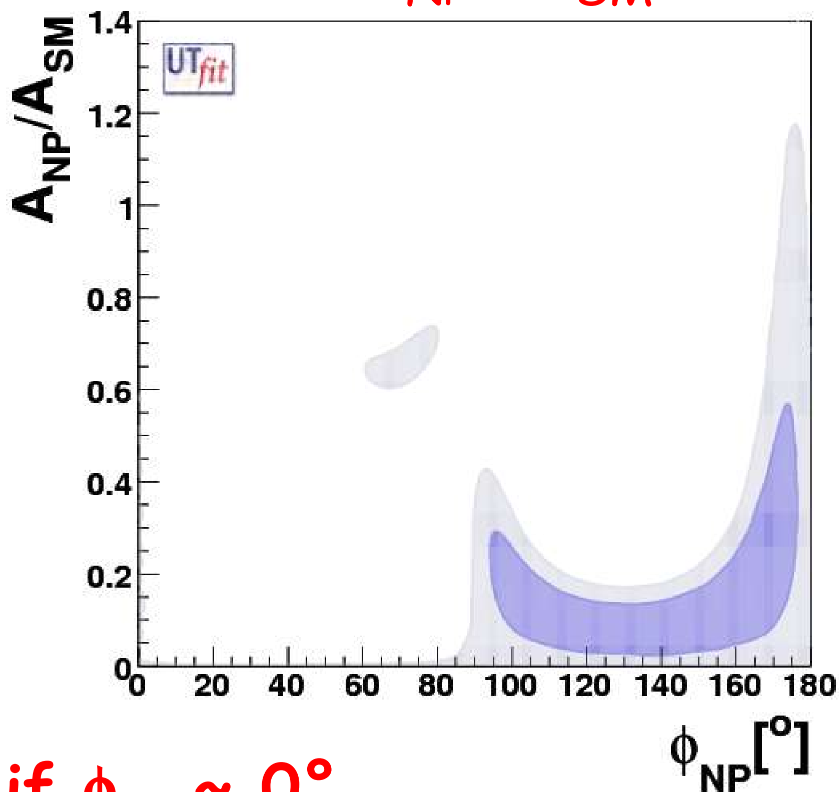
Define

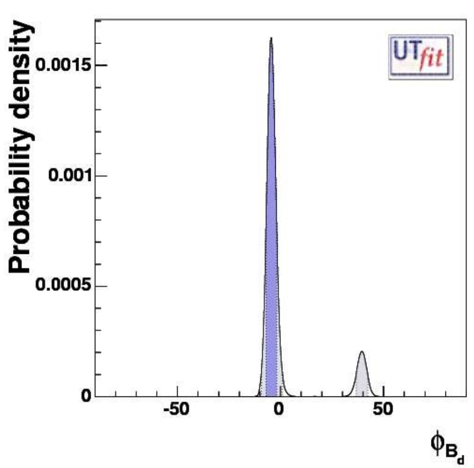
$$C_{B_d} e^{2i\phi_{B_d}} = \frac{A_{SM} e^{2i\beta} + A_{NP} e^{2i(\beta+\phi_{NP})}}{A_{SM} e^{2i\beta}}$$

The UT analysis strongly constrains A_{NP}/A_{SM}:



$C_{Bd} = 1.21 \pm 0.46$





$\phi_{Bd} = (-4.5 \pm 2.6)°$

$A_{NP}/A_{SM} \sim 1$ only if $\phi_{NP} \sim 0°$,
otherwise $A_{NP}/A_{SM} \sim$ 0-20% @ 95% prob.

QUESTION 3) - WHAT HAVE WE LEARNED ON NP?

- New sources of CPV in $s \to d$ and/or $b \to d$ transitions are:
  - strongly constrained by the UT fit
  - "unnecessary", given the great success of the fit
- New sources of CPV in $b \to s$ transitions are
  - much less (un-) constrained by the UT fit
  - Possibly constrained by rare decays & $b \to s$ penguins (model-dependent)

QUESTION 3) - CONTINUED

Two classes of NP models still allowed by data:

1. Models with no new source of flavour & CP violation (Minimal Flavour Violation)
2. Models with new sources of CPV in $b \to s$ transitions
   - natural in many flavour models, given the strong breaking of family SU(3)

     Pomarol, Tommasini; Barbieri, Dvali, Hall; Barbieri, Hall; Barbieri, Hall, Romanino; Berezhiani, Rossi; Masiero et al; …
   - hinted at by ν's in SUSY-GUTs

     Baek et al.; Moroi; Akama et al.; Chang, Masiero, Murayama; Hisano, Shimizu; Goto et al.; …

MINIMAL FLAVOUR VIOLATION

Gabrielli, Giudice, NPB433; Buras et al., PLB500; D'Ambrosio et al., NPB 645; Bobeth et al., hep-ph/0505110

1) No new source of flavour and CP violation

- NP contributions also governed by Yukawas
- NP only modifies SM top contribution to FCNC & CPV

2a) One Higgs or small/moderate $\tan\beta$

- No new operators, full correlations among K & B decays

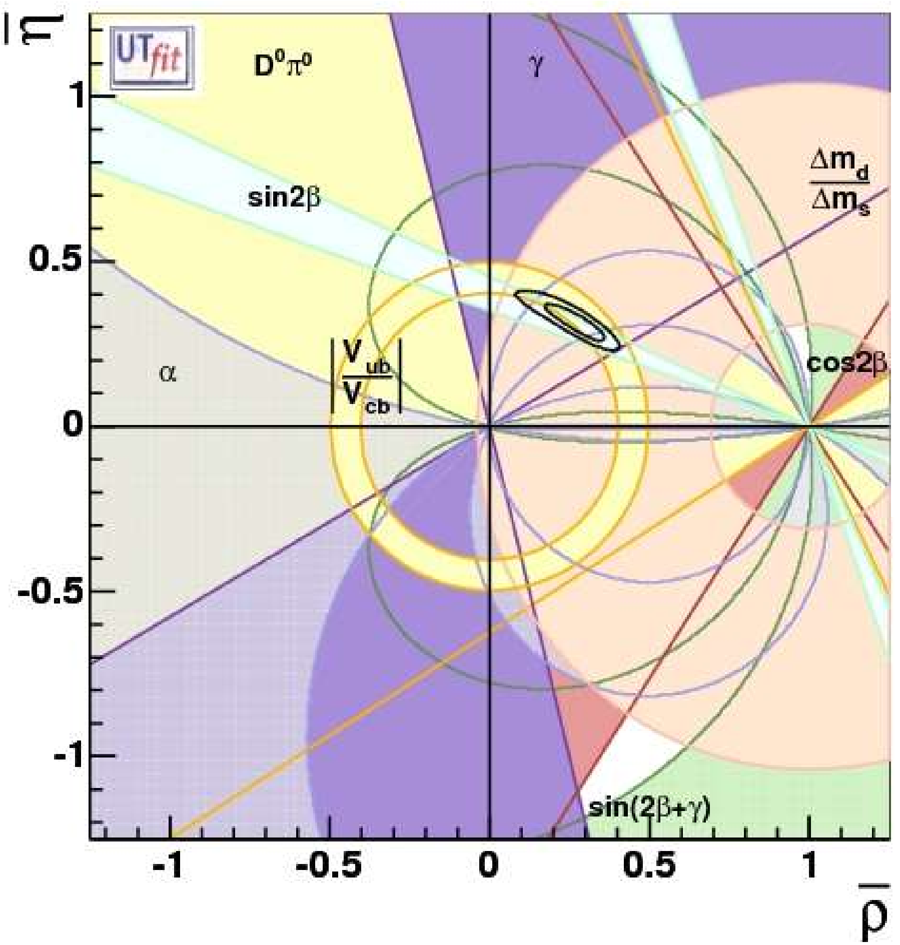
2b) Large $\tan\beta$

- New operators, less correlations among K & B decays

The Universal Unitarity Triangle

Buras et al., PLB500

Angle measurements + $\Delta M_d/\Delta M_s$ unaffected by NP in MFV



$\bar{\rho}$	0.258 ± 0.066	$[0.107,\ 0.373]$
$\bar{\eta}$	0.319 ± 0.039	$[0.249,\ 0.398]$
$\sin 2\beta$	0.726 ± 0.028	$[0.668,\ 0.778]$
$\alpha[^\circ]$	105 ± 11	$[81,\ 123]$
$\gamma[^\circ]$	51 ± 10	$[34,\ 74]$
$(2\beta+\gamma)[^\circ]$	98 ± 12	$[78,\ 122]$

valid in any MFV model
for any value of tanβ

UTfit Coll., hep-ph/0509xxx

UUT starting point for MFV studies of rare decays

Bobeth, Bona, Buras, Ewerth, Pierini, L.S., Weiler, hep-ph/0505110

Identify leading NP contributions:

1) dimension 4 operators: FCNC effective Z vertex

$\Rightarrow C = C_{SM} + \Delta C$

2) dimension 5 operators: (chromo)magnetic penguin

$\Rightarrow C_7^{eff} = (C_7^{eff})_{SM} + \Delta C_7^{eff}$

3) dimension 6 operators: penguins, boxes

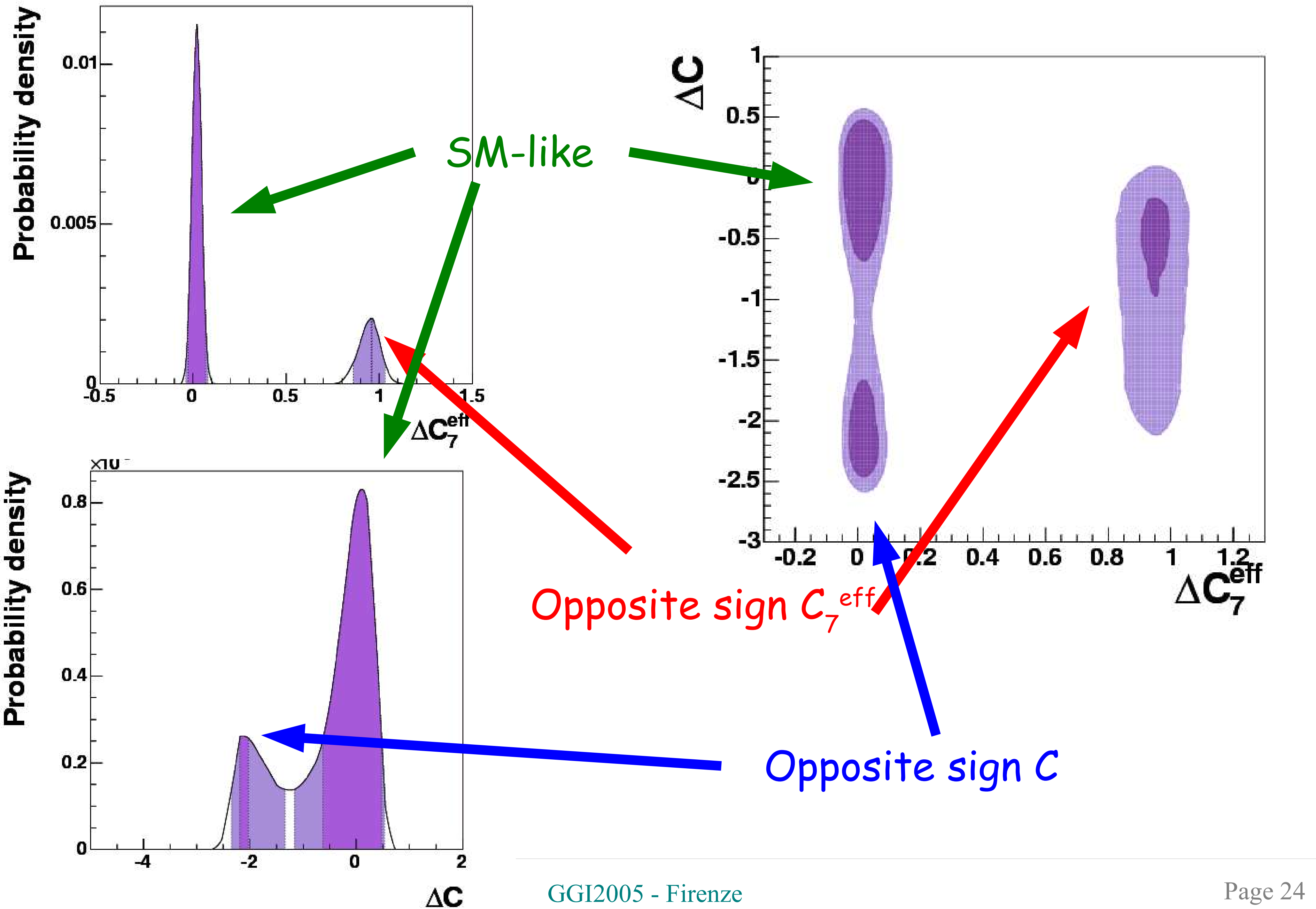
$\Rightarrow$ subleading NP contributions to rare decays

Rare decays $\Leftrightarrow$ SM functions + ΔC, ΔC_7^{eff}

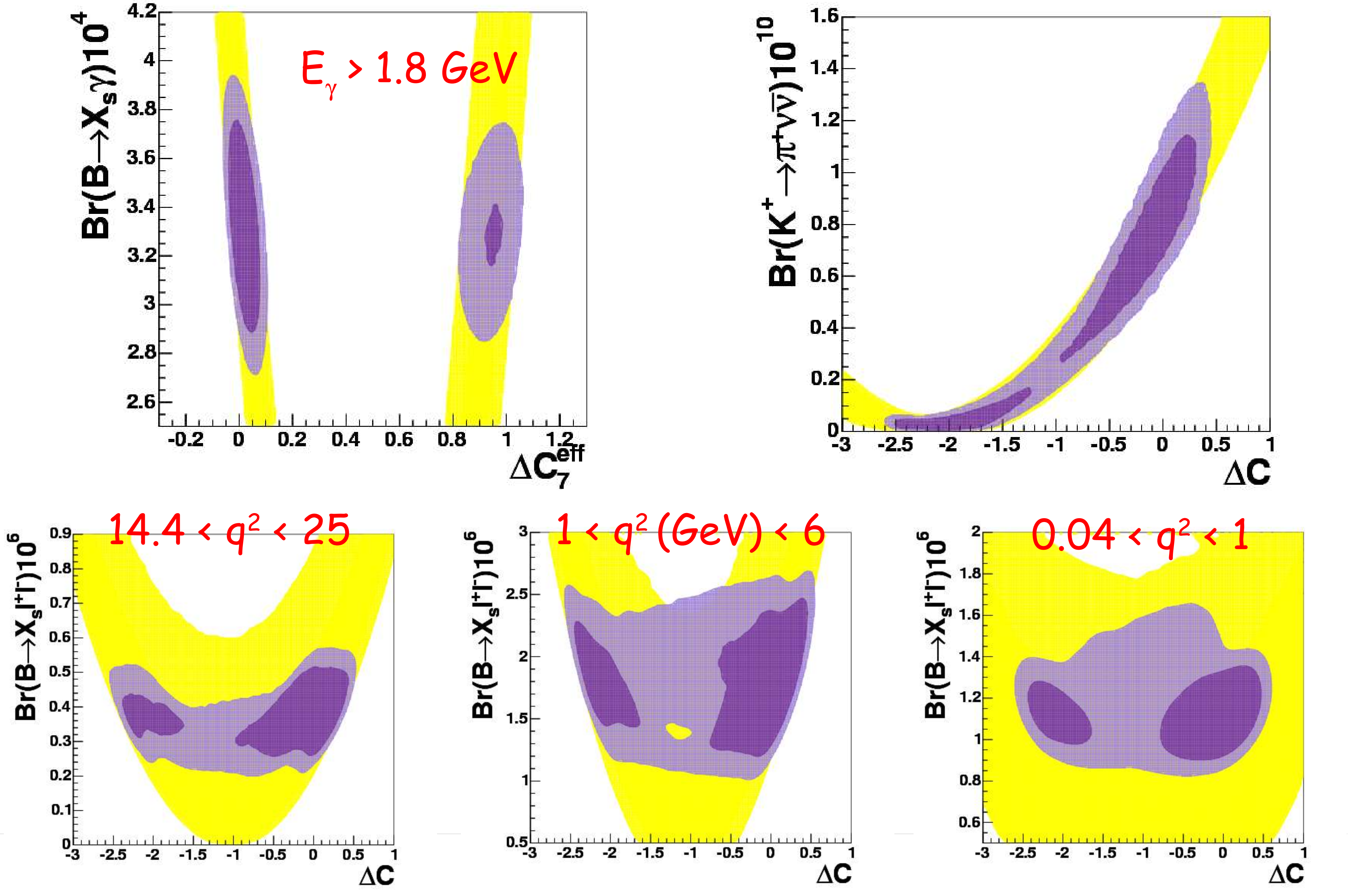
RARE DECAYS IN MFV

- ρ, η from the UUT analysis
- ΔC_7^{eff} can be constrained using $BR(B \to X_s \gamma)$
- ΔC can be constrained using $BR(B \to X_s l^+ l^-)$ and $BR(K^+ \to \pi^+ \nu\nu)$
- Get predictions for all other rare decays

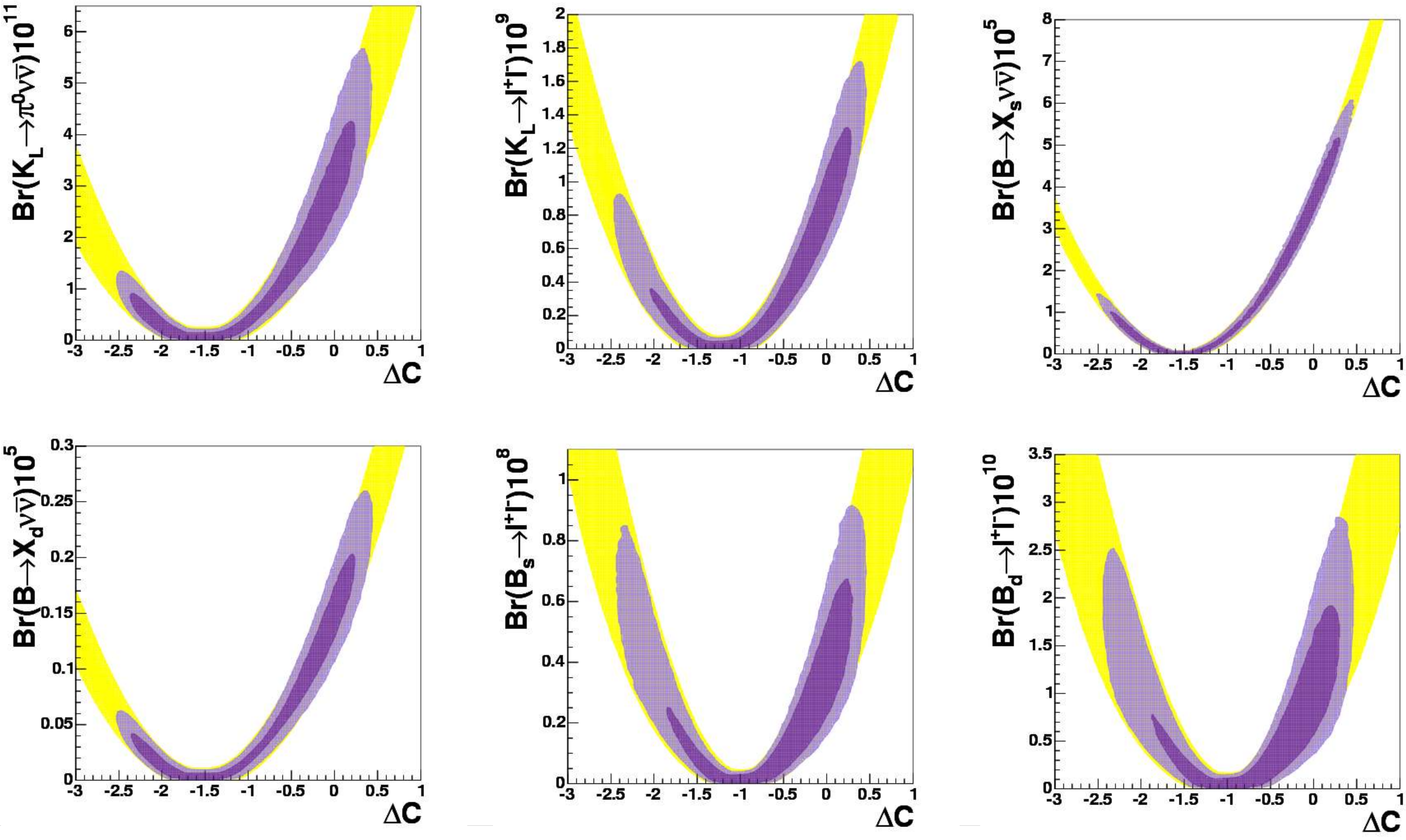
CONSTRAINTS ON NP



NP CONTRIBUTIONS vs EXP CONSTRAINTS



ANSWER TO QUESTION 4) - PREDICTIONS FOR RARE DECAYS

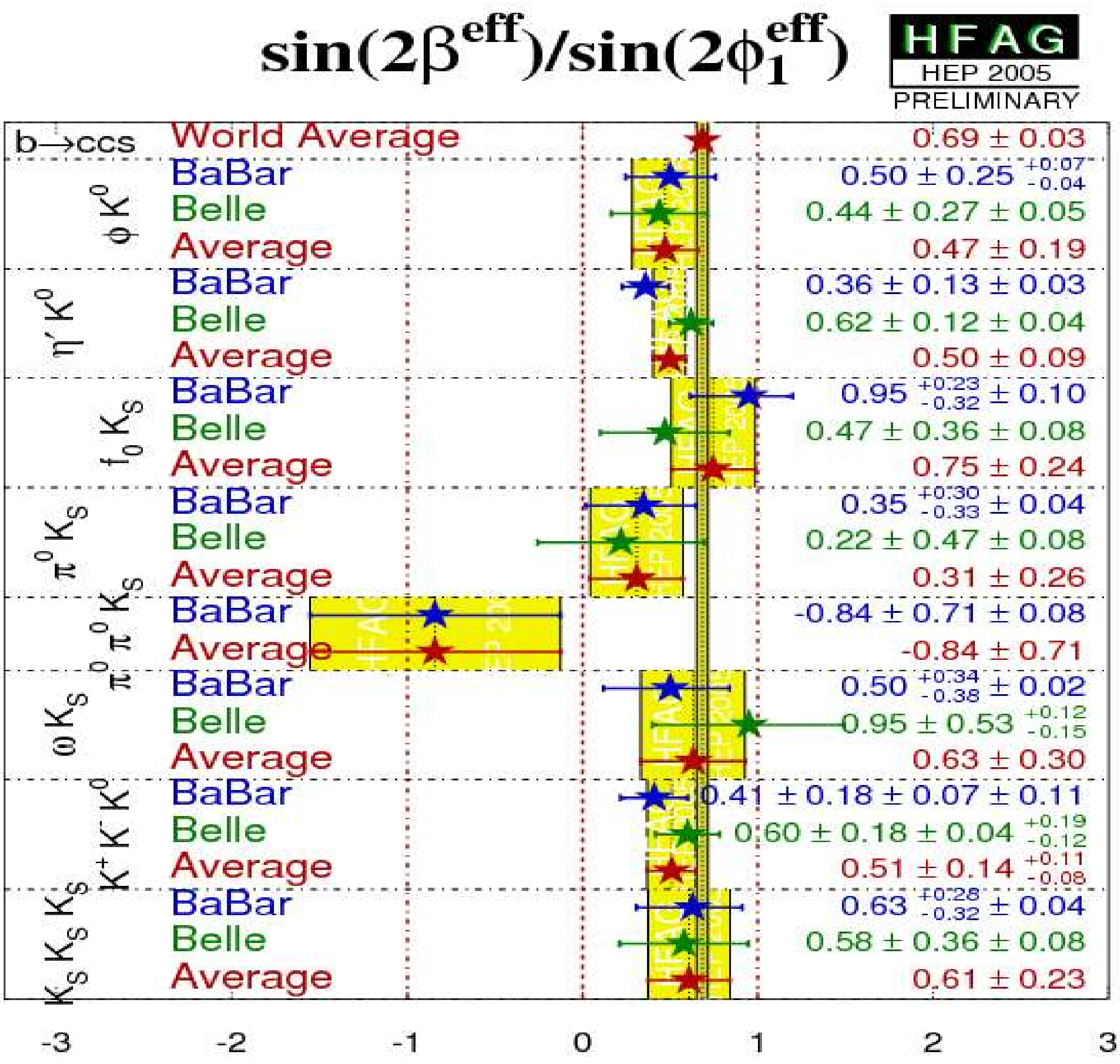


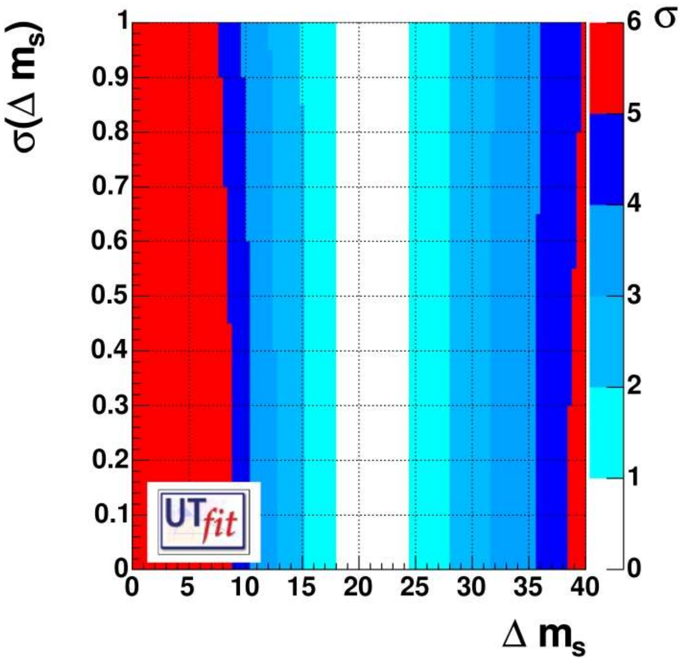
UPPER BOUNDS ON RARE DECAYS:

Branching Ratios	MFV (95%)	SM (68%)	SM (95%)	exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11}$	< 11.9	8.3 ± 1.2	$[6.1, 10.9]$	$(14.7^{+13.0}_{-8.9})$ [19]
$Br(K_L \to \pi^0 \nu\bar{\nu}) \times 10^{11}$	< 4.59	3.08 ± 0.56	$[2.03, 4.26]$	$< 5.9 \cdot 10^4$ [37]
$Br(K_L \to \mu^+\mu^-)_{SD} \times 10^9$	< 1.36	0.87 ± 0.13	$[0.63, 1.15]$	-
$Br(B \to X_s \nu\bar{\nu}) \times 10^5$	< 5.17	3.66 ± 0.21	$[3.25, 4.09]$	< 64 [38]
$Br(B \to X_d \nu\bar{\nu}) \times 10^6$	< 2.17	1.50 ± 0.19	$[1.12, 1.91]$	-
$Br(B_s \to \mu^+\mu^-) \times 10^9$	< 7.42	3.67 ± 1.01	$[1.91, 5.91]$	$< 2.7 \cdot 10^2$ [39]
$Br(B_d \to \mu^+\mu^-) \times 10^{10}$	< 2.20	1.04 ± 0.34	$[0.47, 1.81]$	$< 1.5 \cdot 10^3$ [39]

In MFV models (at low/moderate tan β) rare decays can be only slightly enhanced w.r.t the SM. Strong suppressions still possible at present.

The last resort: NP in $b \to s$ modes





Δm_s > 31(38) ps^{-1}

is new physics @3(5)σ

The SUSY option

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;…

- Well-motivated extension of the SM
- SUSY flavour models, SUSY-GUTS & neutrino oscillations point towards possibly large b-s mixing in the squark sector

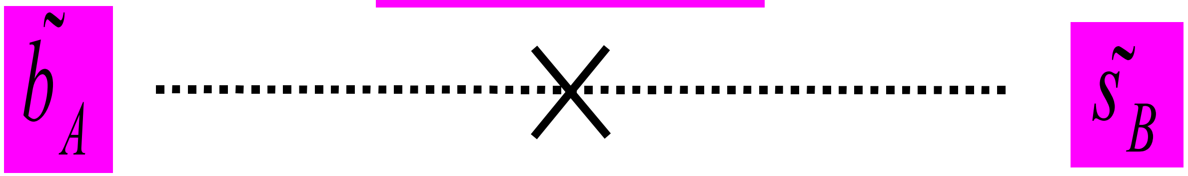
A Model-Independent Analysis

Ciuchini et al., in progress - Preliminary!!

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

$$\left(\delta^{d}{}_{23}\right)_{AB}$$

Think of δ's as SUSY equivalent of CKM mixing



four insertions AB=LL, LR, RL, RR

CONSTRAINTS ON δ's

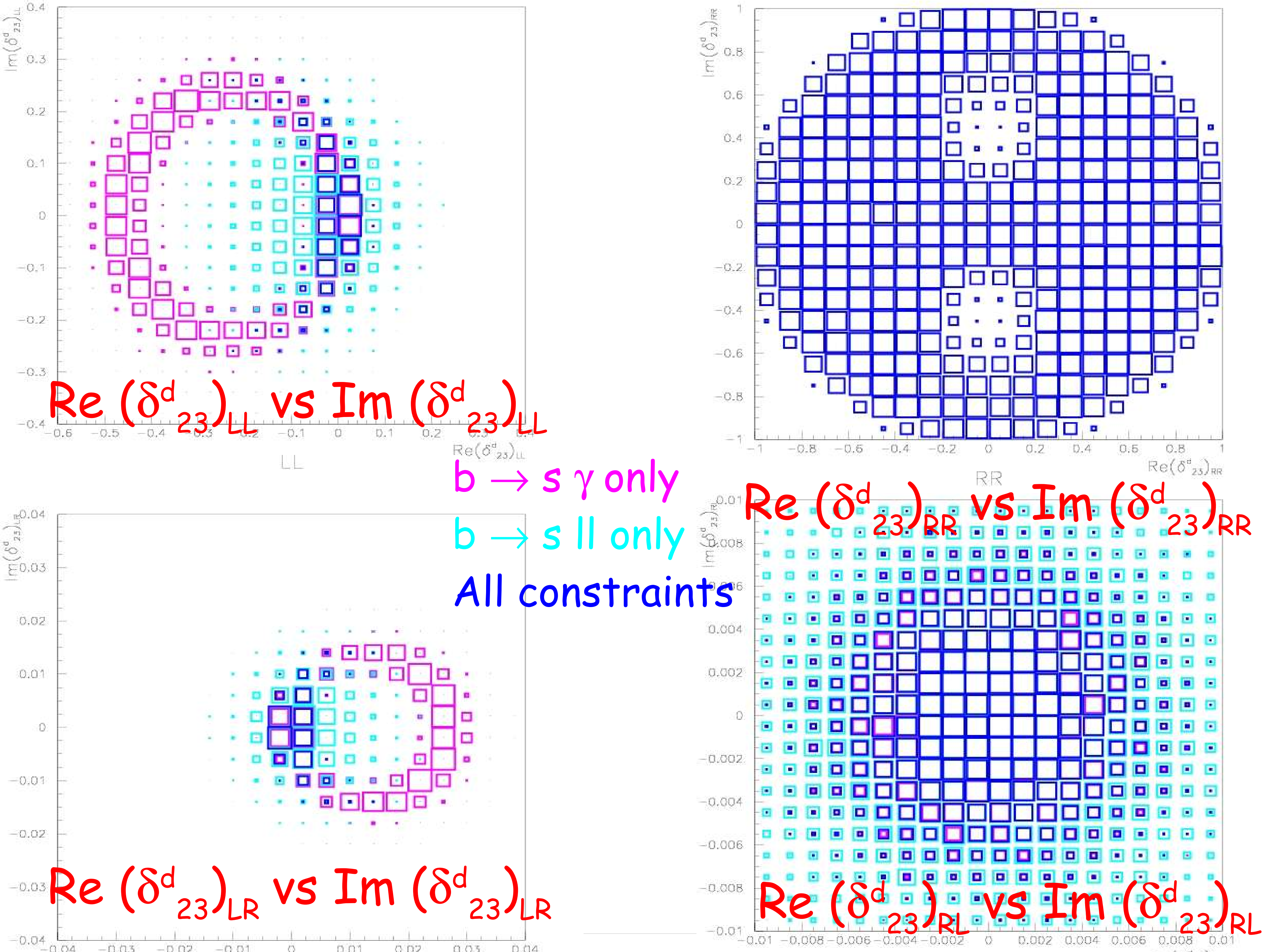
- gluinos contribute to rare decays only through (chromo)magnetic penguins - (electro)penguin operators suppressed

Bertolini et al., NPB353; Gabbiani et al., NPB477; Buras, Romanino, L.S., NPB520

- very strong constraints from combination of $b \to s\gamma$ and $b \to s\, l^+ l^-$ (both dominated by C_7^{eff})

Ciuchini et al, PRD67; Hiller, PRD69; Gambino, Haisch, Misiak, PRL94

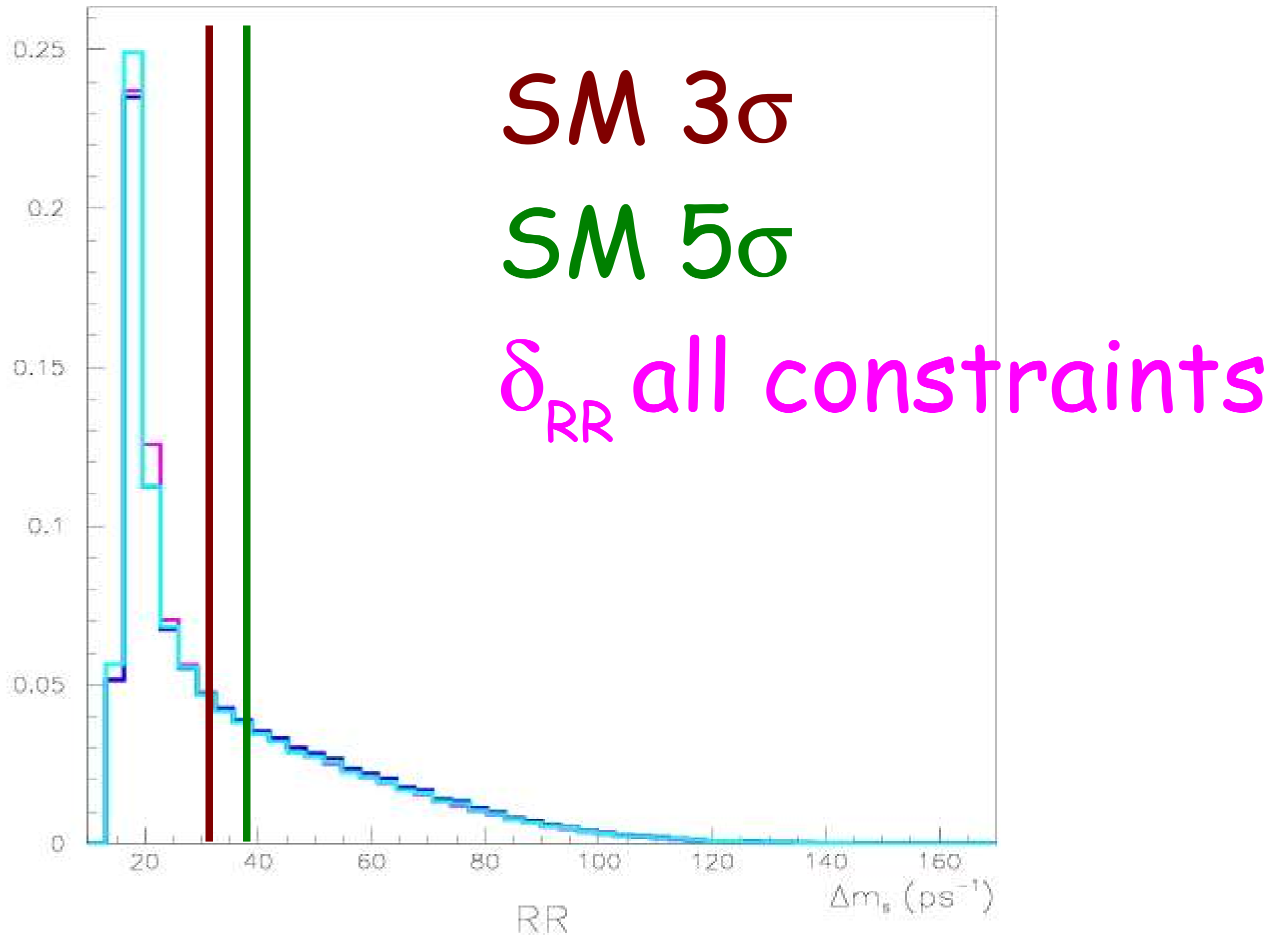
- Use $m_{gl} = m_{sq} = -\mu = 350$ GeV, $\tan\beta = 10$



Re (δ^d_23)_LL vs Im (δ^d_23)_LL
Re (δ^d_23)_RR vs Im (δ^d_23)_RR
Re (δ^d_23)_LR vs Im (δ^d_23)_LR
Re (δ^d_23)_RL vs Im (δ^d_23)_RL
b → s γ only
b → s ll only
All constraints
LL
RR
LR
RL

ANSWER TO QUESTION 4) - THE ΔM_s EXAMPLE

ΔM_s :

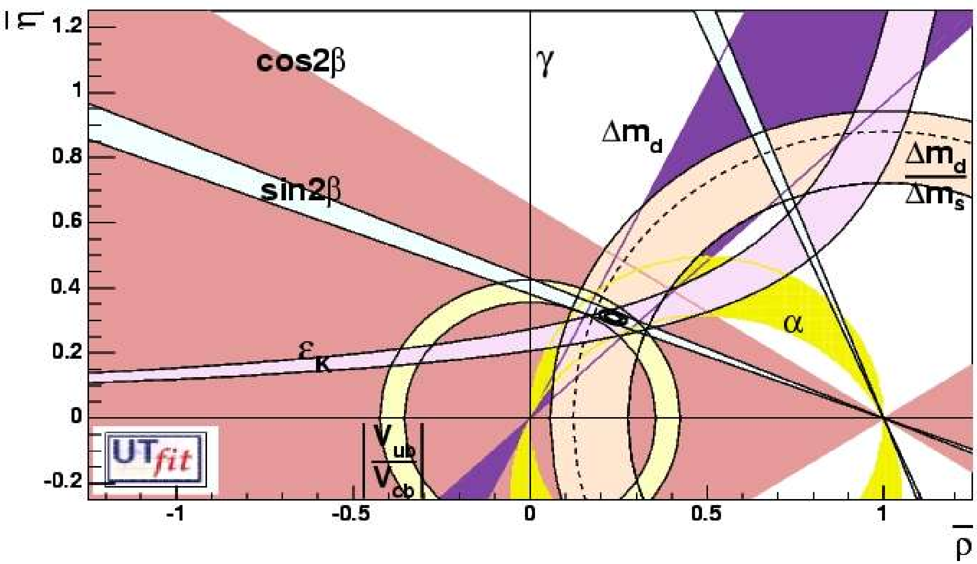


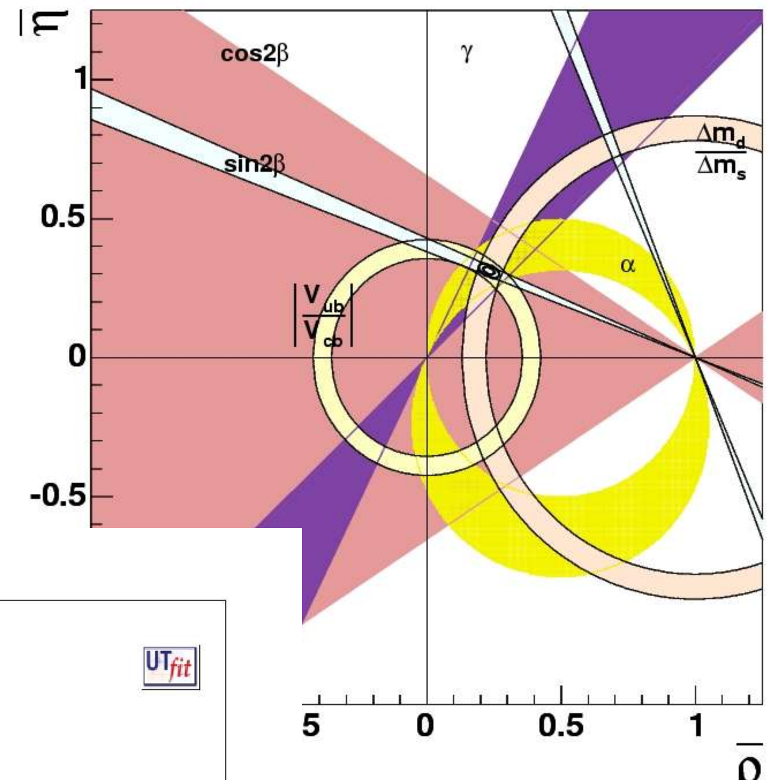
Large values of ΔM_s possible for RR (and LL @ low tan β), with large values of mixing phase $\Leftrightarrow$ CPV in $B_s \rightarrow \psi\phi$, $D_s^+ D_s^-$

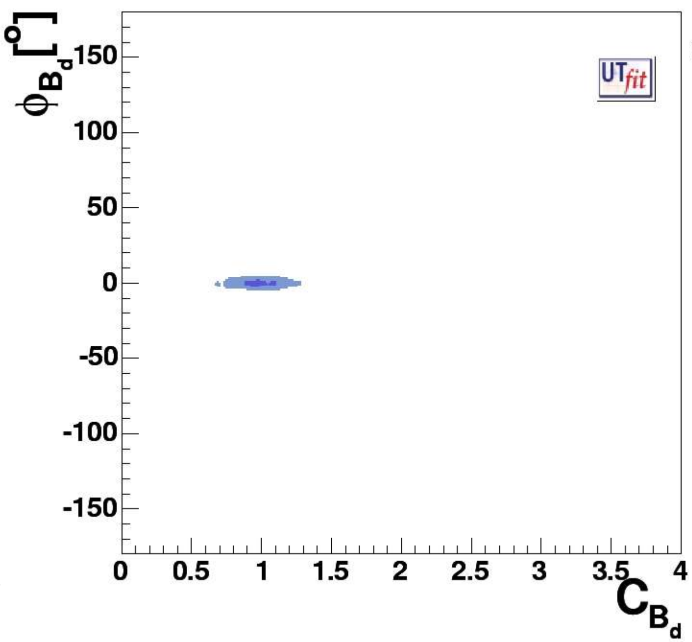
Conclusions

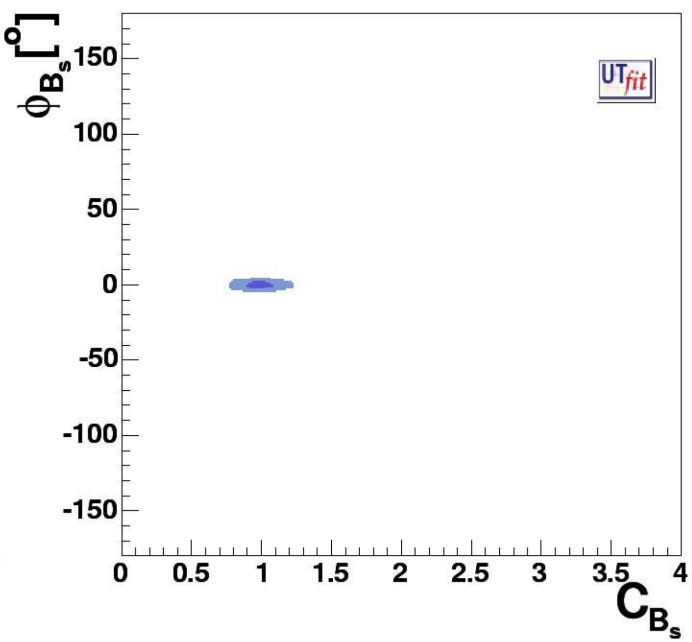
- The SM is (surprisingly enough) extremely successful in reproducing all available data
- Thanks to the recent progress, NP in $\Delta B=2$ and $\Delta S=2$ transitions is strongly constrained, pointing towards MFV
- Surprises (from SUSY) still possible in $b \to s$ transitions, though rare decays are getting tighter and tighter
- Hadron colliders will tell us whether SM, MFV or New Flavour & CPV in $b \to s$ ...

OUTLOOK: 2010









Or, hopefully, something different...

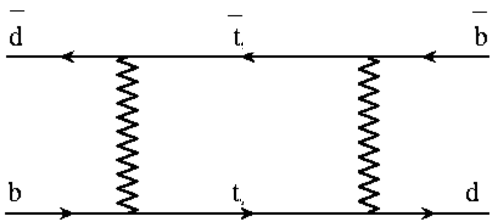
BACKUP SLIDES

MFV: an effective theory approach

D'Ambrosio et al., hep-ph/0207036

- classification of the dim-6 operators built with the SM fields and 1 or 2 Higgs doublets under the assumption that the flavour violation dynamics is determined by ordinary Yukawa couplings

1H: Universal NP effect in the $\Delta F=2$ Inami-lim function of the top

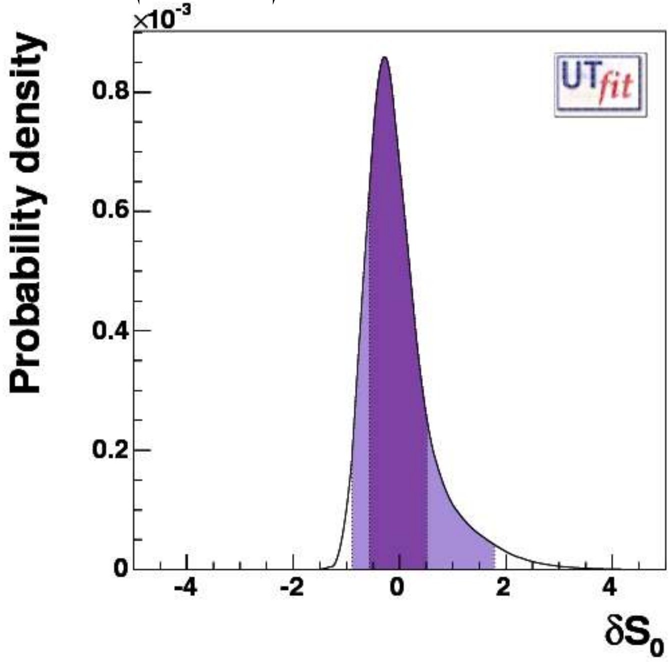


$$S_0(x_t) \rightarrow S_0(x_t) + \delta S_0, \quad |\delta S_0| = O\left(4\frac{\Lambda_0^2}{\Lambda^2}\right), \quad \Lambda_0 \sim 2.4 \text{ TeV}$$

We can bound the NP scale Λ:

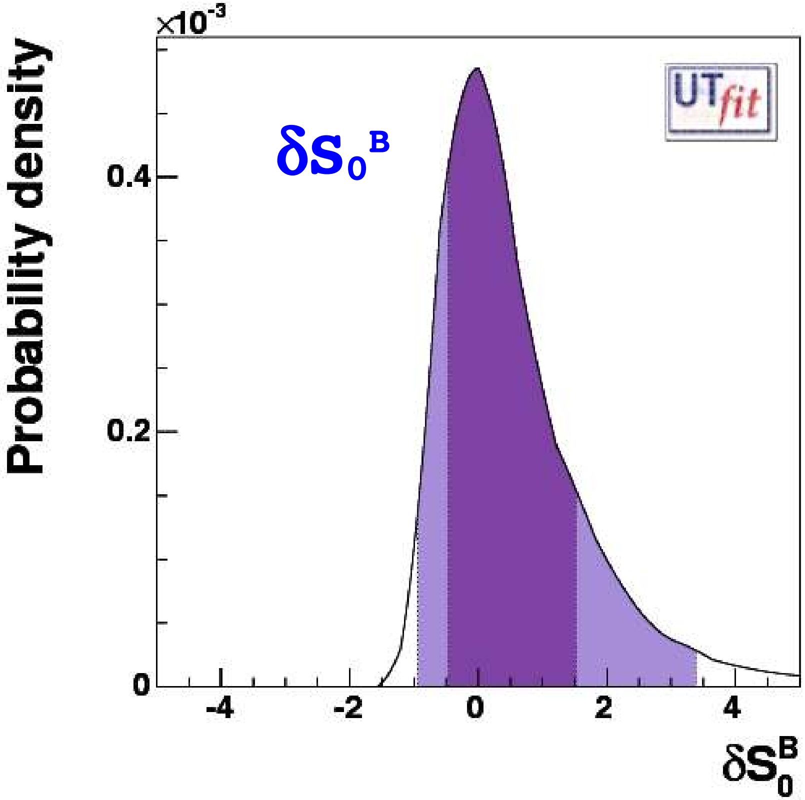
Λ > 5.1 TeV @95% prob. for positive δS_0

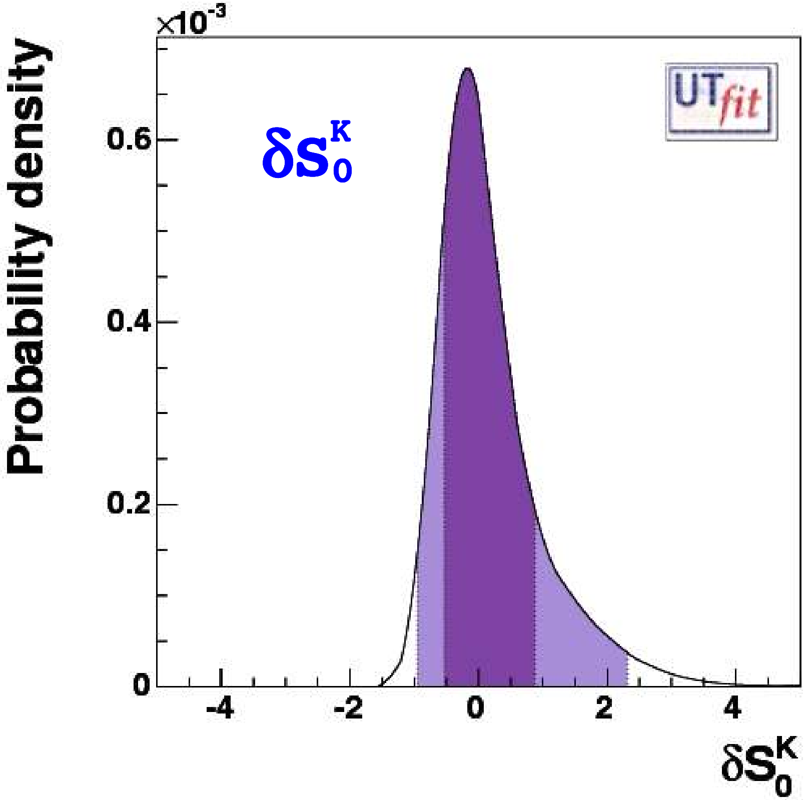
Λ > 3.6 TeV @95% prob. for negative δS_0



2H + large tanβ: terms proportional to the bottom Yukawa coupling are enhanced and cannot be neglected any more

$$\delta S_0^B \neq \delta S_0^K$$



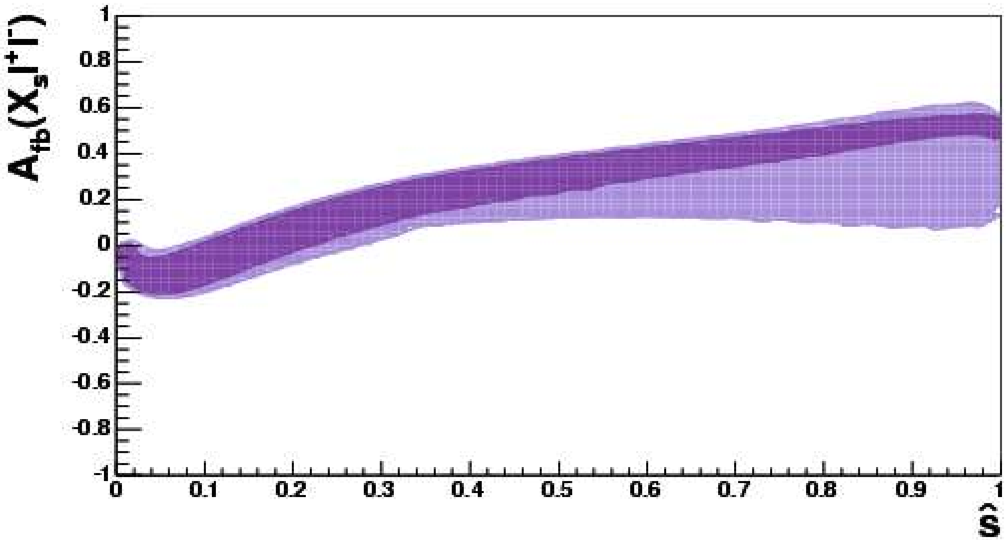


Λ > 2.6 TeV @95% prob. for $\delta S_0 > 0$
Λ > 4.9 TeV @95% prob. for $\delta S_0 < 0$

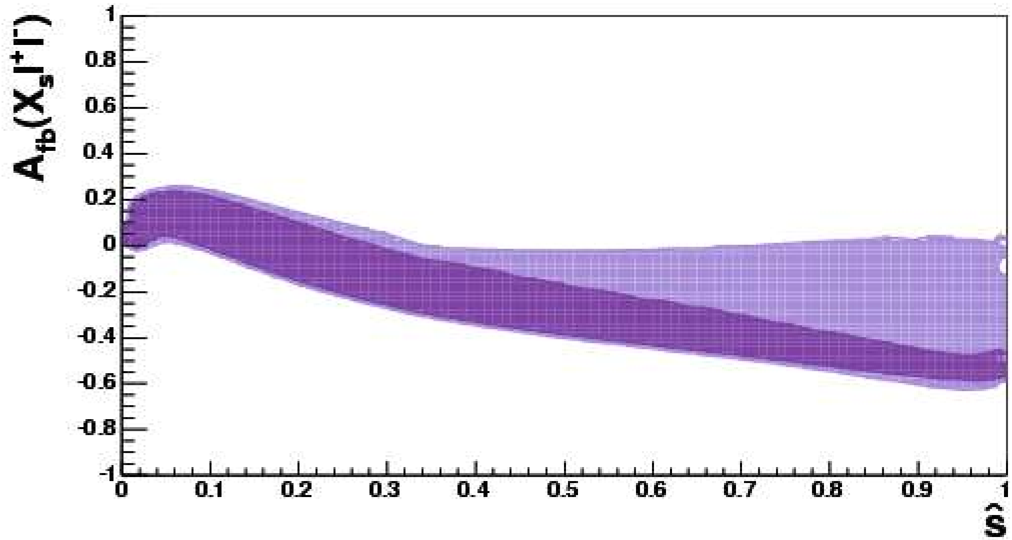
Λ > 3.2 TeV @95% prob. for $\delta S_0 > 0$
Λ > 4.9 TeV @95% prob. for $\delta S_0 < 0$

FORWARD-BACKWARD ASYMMETRY IN $B \to X_s l^+ l^-$

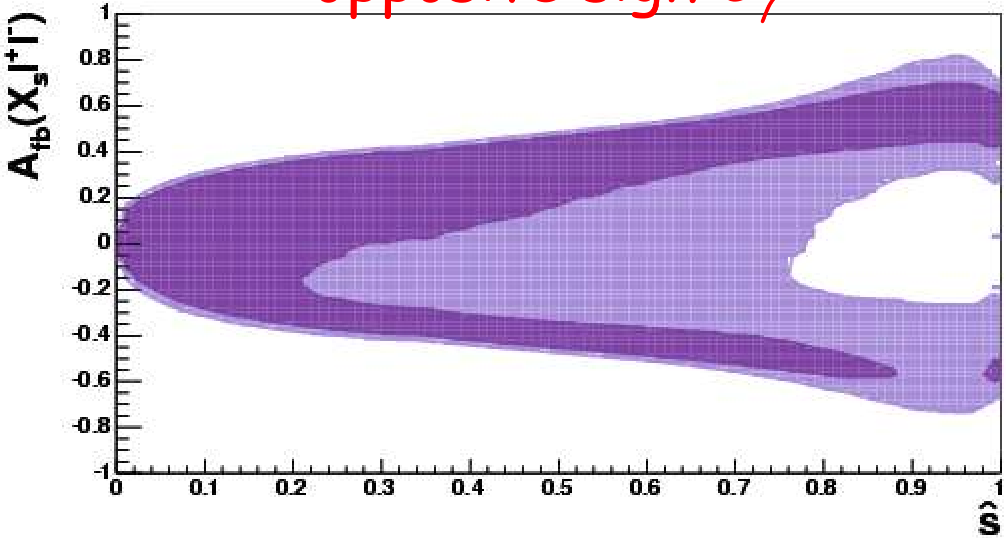
C_7^{eff}, C SM-like



opposite sign C



opposite sign C_7^{eff}



Can we estimate NP contributions to $B \to (\phi,\eta,\omega,\pi)\ K_S$?

- Realistic studies of NP effects in these modes should take into account:
  - Hadronic uncertainties in computation of decay amplitudes $\to$ model dependent
  - Correlation with other $b \to s$ observables: $b \to s\,\gamma$, $b \to s\, l^+ l^-$, $B \to K\pi$, ΔM_s, etc.

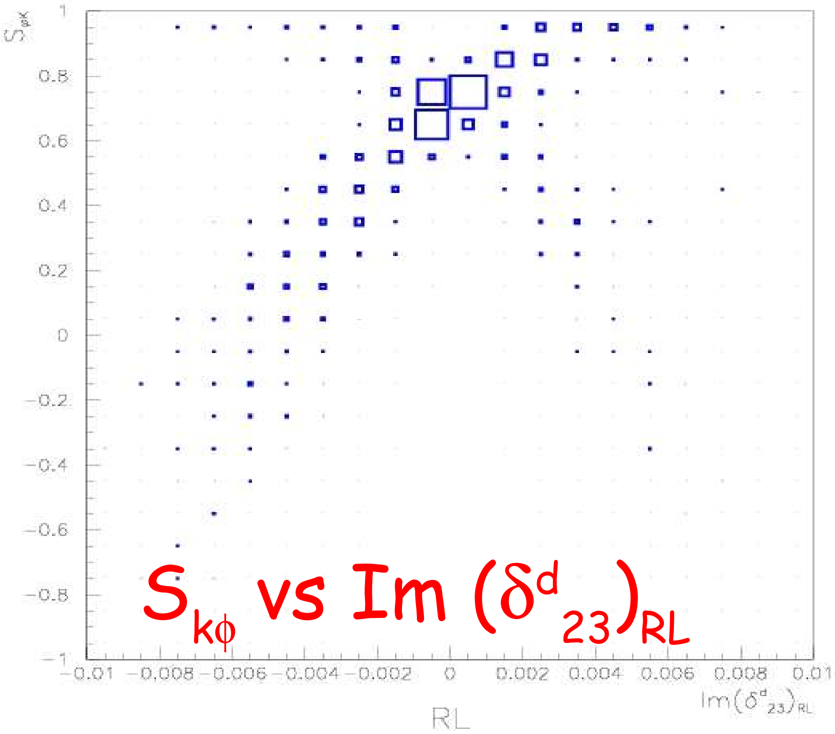
    $\to$ very stringent by now

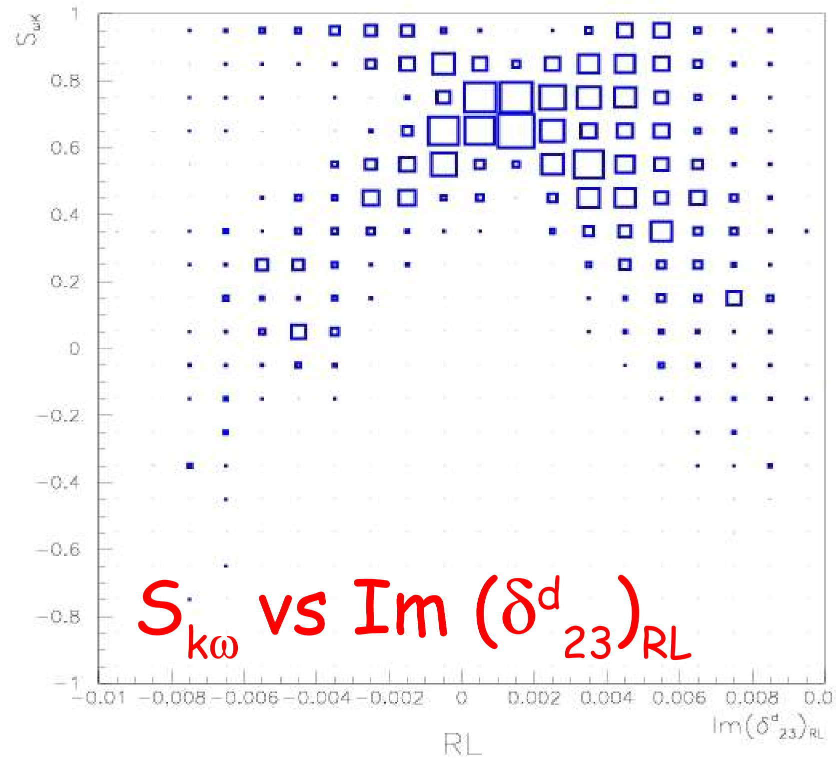
PREDICTIONS FOR $\sin 2\beta^{eff}$

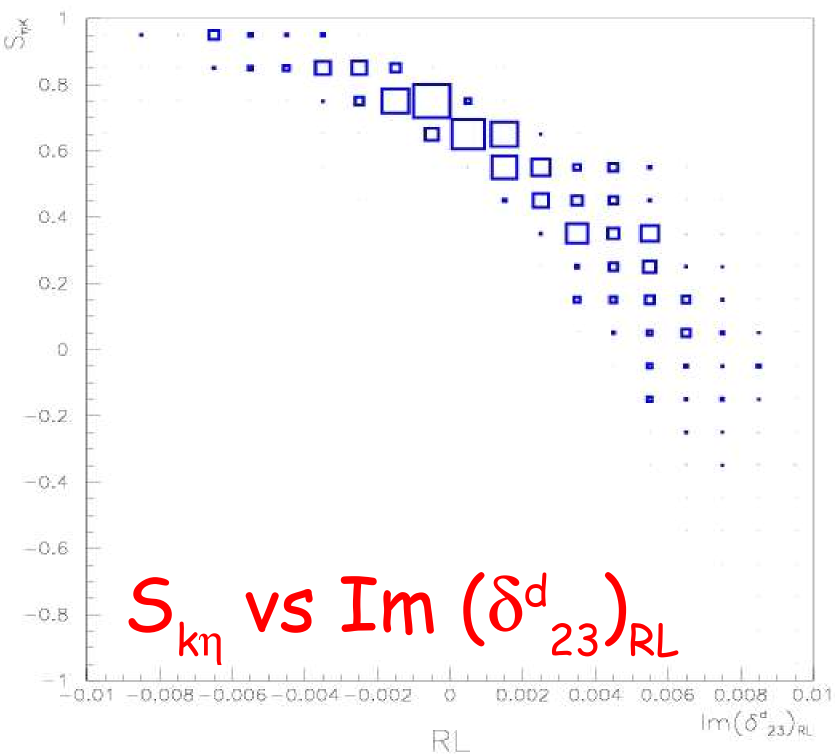
- To be generous with SUSY, use QCD factorization with enlarged range for power-suppressed corrections - Model dependent, large uncertainties

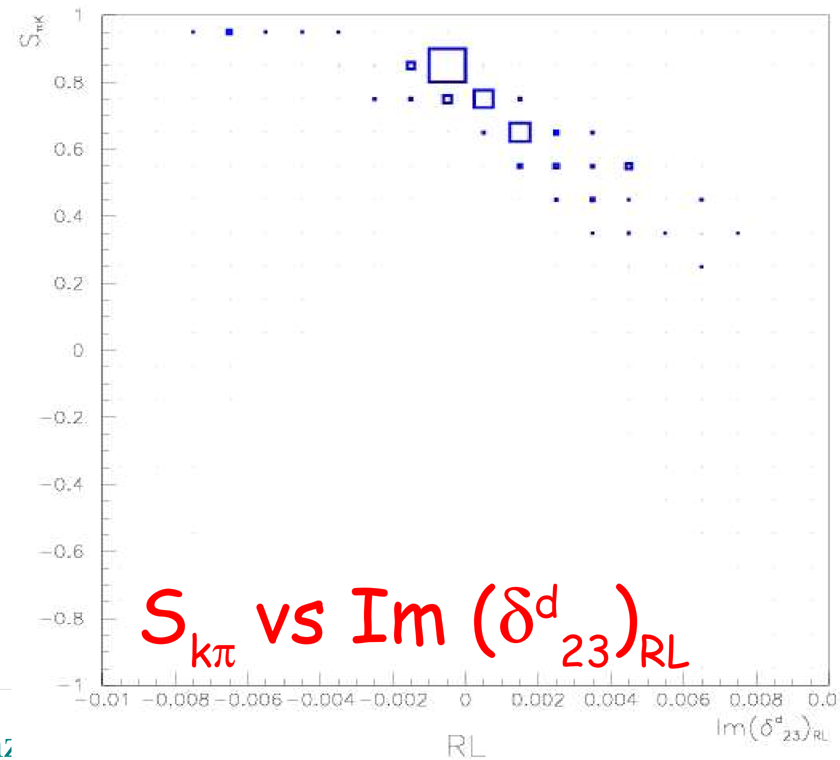
  Beneke et al., PRL83, NPB606, NPB675; Ciuchini et al., PLB515, PRD67.

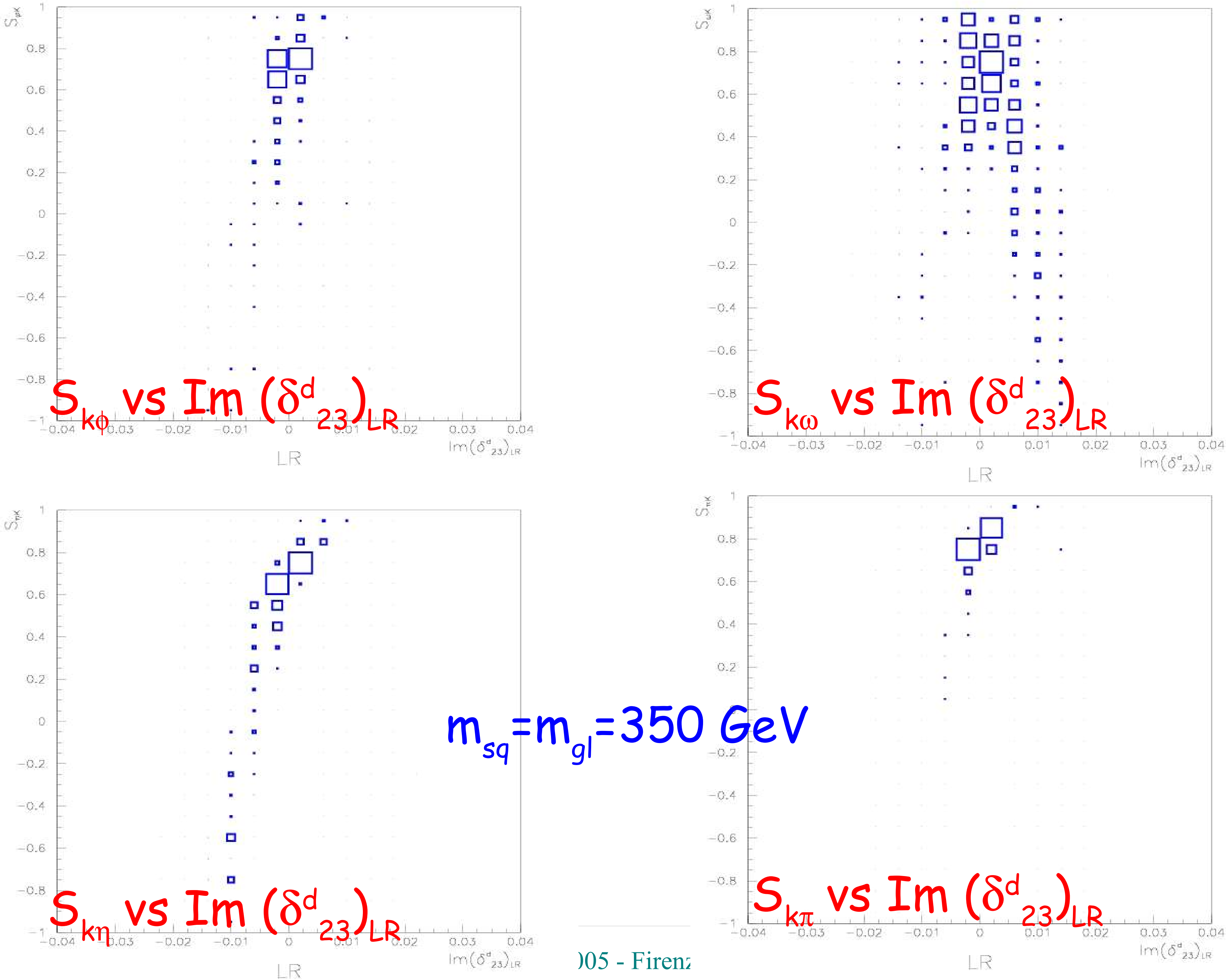
- impose agreement with BR's and direct CP violation
- As an example, results in the RL case


$S_{k\phi}$ vs Im $(\delta^d{}_{23})_{RL}$
$S_{\phi K}$
$Im(\delta^d{}_{23})_{RL}$

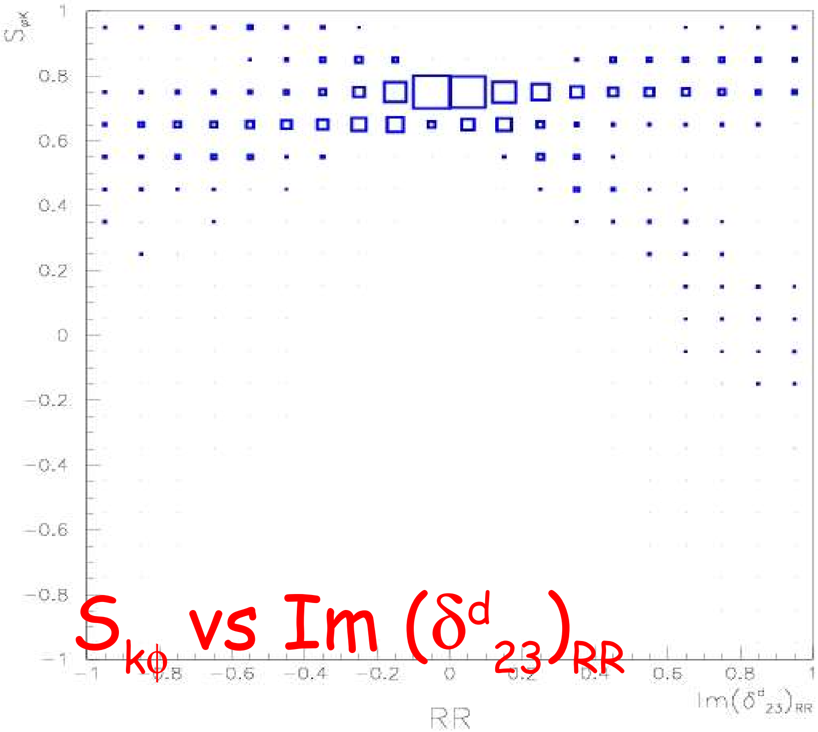

$S_{k\omega}$ vs Im $(\delta^d{}_{23})_{RL}$
$S_{\omega K}$
$Im(\delta^d{}_{23})_{RL}$

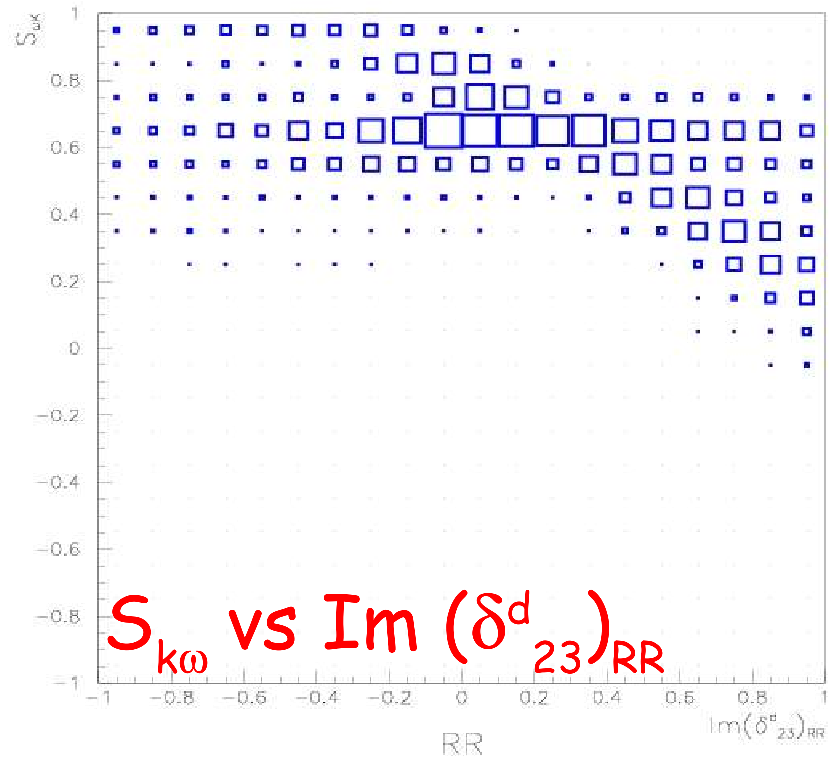

$S_{k\eta}$ vs Im $(\delta^d{}_{23})_{RL}$
$S_{\eta K}$
$Im(\delta^d{}_{23})_{RL}$


$S_{k\pi}$ vs Im $(\delta^d{}_{23})_{RL}$
$S_{\pi K}$
$Im(\delta^d{}_{23})_{RL}$

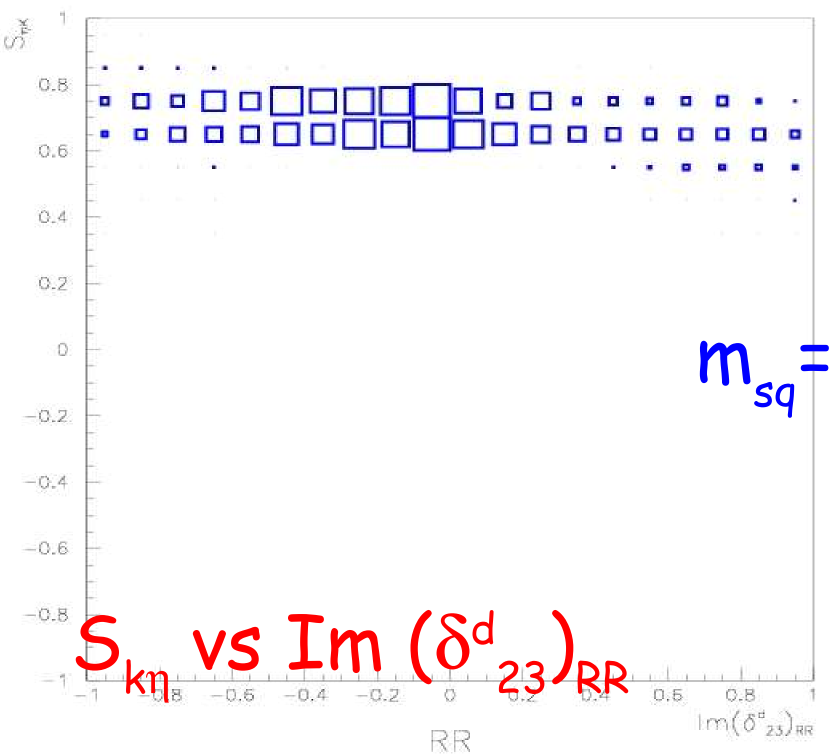


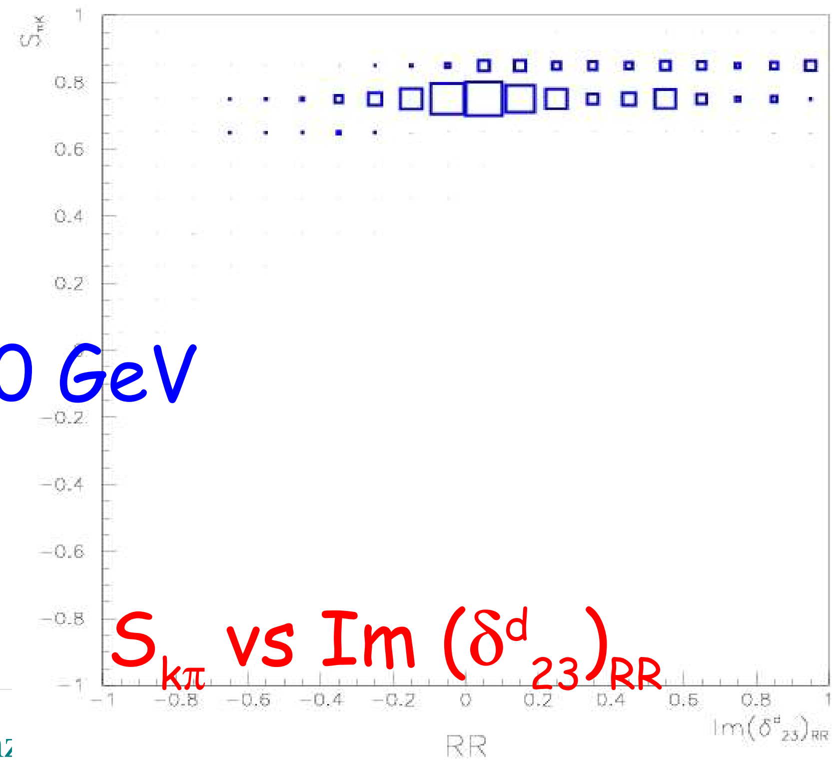
$S_{k\phi}$ vs Im $(\delta^d_{23})_{LR}$
$S_{k\omega}$ vs Im $(\delta^d_{23})_{LR}$
$S_{k\eta}$ vs Im $(\delta^d_{23})_{LR}$
$S_{k\pi}$ vs Im $(\delta^d_{23})_{LR}$
$m_{sq}=m_{gl}=350$ GeV
$Im(\delta^d_{23})_{LR}$
LR

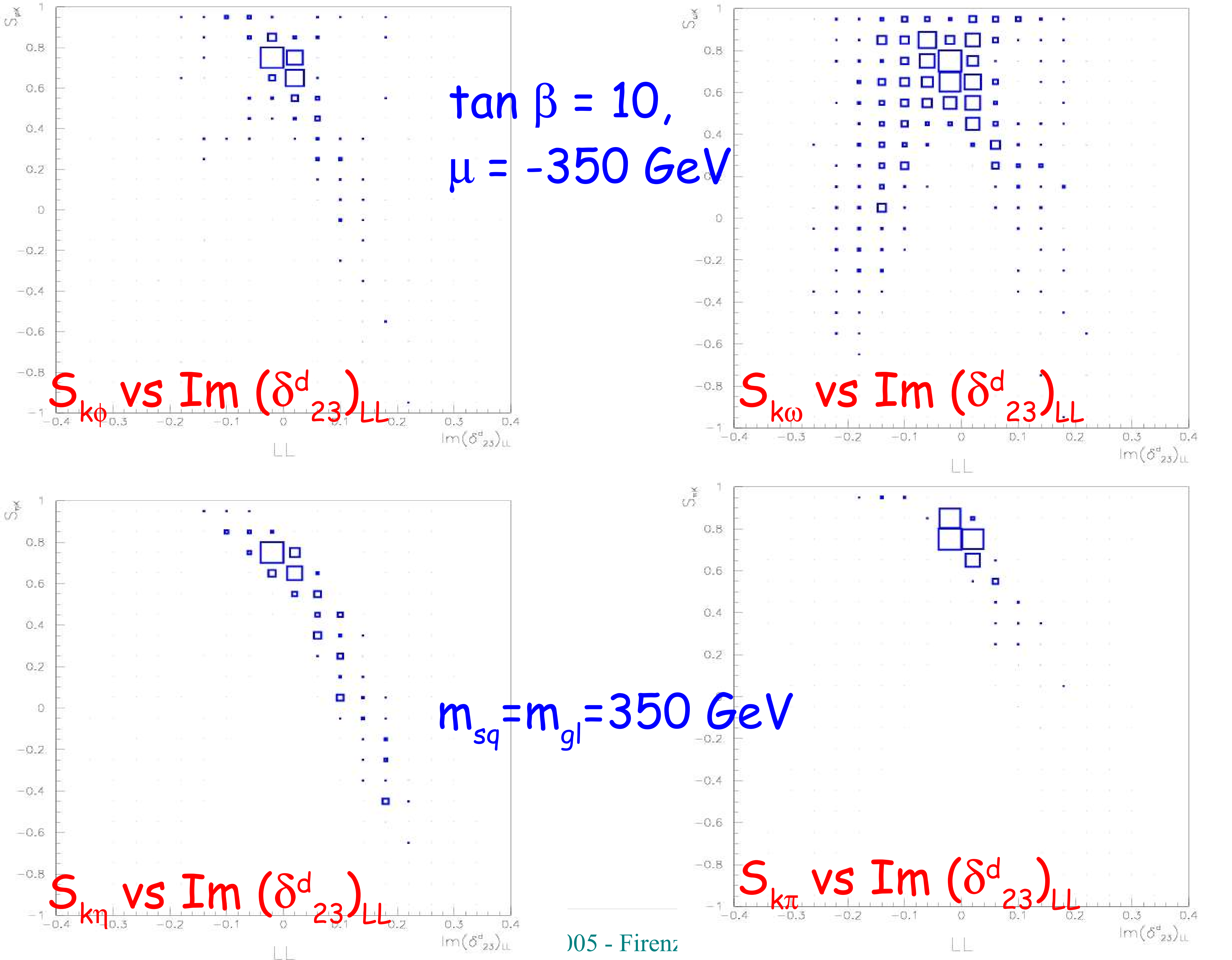




$m_{sq}=m_{gl}=350$ GeV







tan β = 10,
μ = -350 GeV
$S_{k\phi}$ vs Im $(\delta^d_{23})_{LL}$
$S_{k\omega}$ vs Im $(\delta^d_{23})_{LL}$
$m_{sq}=m_{gl}=350$ GeV
$S_{k\eta}$ vs Im $(\delta^d_{23})_{LL}$
$S_{k\pi}$ vs Im $(\delta^d_{23})_{LL}$
Im$(\delta^d_{23})_{LL}$
LL