Angles and Mixings

Marco Ciuchini

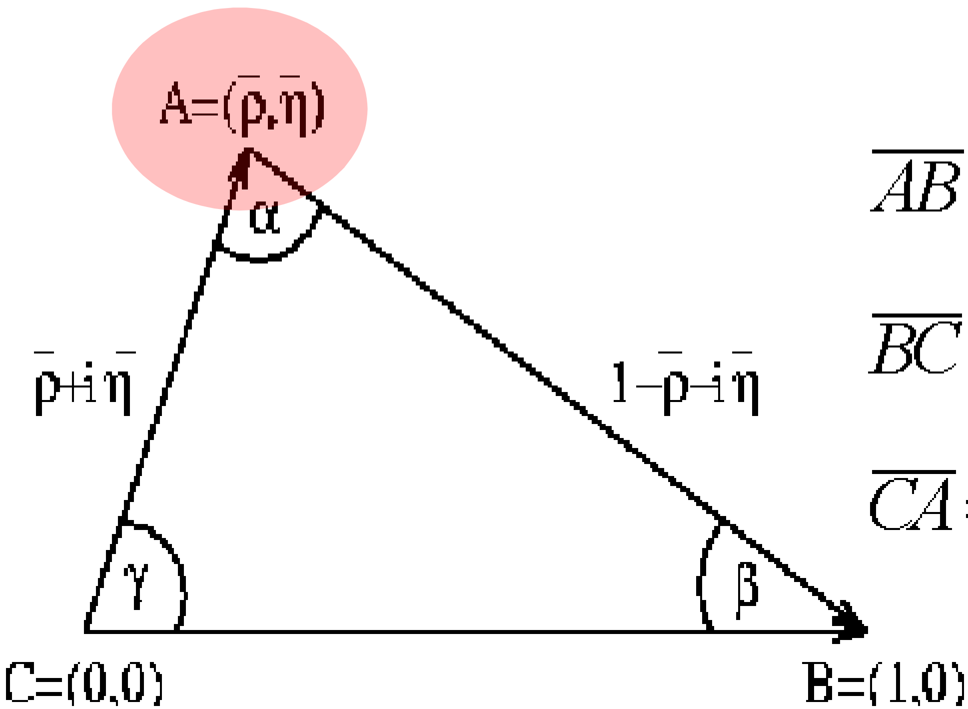
INFN Roma Tre

- UT angles from "tree" decays
  - γ from B -> D K-like modes
  - α from B -> $\pi\pi$ / $\rho\pi$ / $\rho\rho$ modes
  - β from B -> J/ψ K-like modes
- UT angles from penguin decays
  - β from b -> s penguin transitions
- neutral meson mixings
  - (B_d-$\bar{B}_d$ mixing)
  - B_s-$\bar{B}_s$ mixing: Δm_s and ϕ_{Bs}
  - an "intruder": D-$\bar{D}$ mixing

Unitarity Triangle

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

$$V=\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$



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

$$\overline{BC}=1$$

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

Triangle

sides ↔ angles

$|VV^{*}|\leftrightarrow\alpha,\beta,\gamma$

$$\alpha\equiv\arg\left(-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right),\quad \beta\equiv\arg\left(-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right),\quad \gamma\equiv\arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

γ from B -> $D^{(*)}K$

- **no penguins**

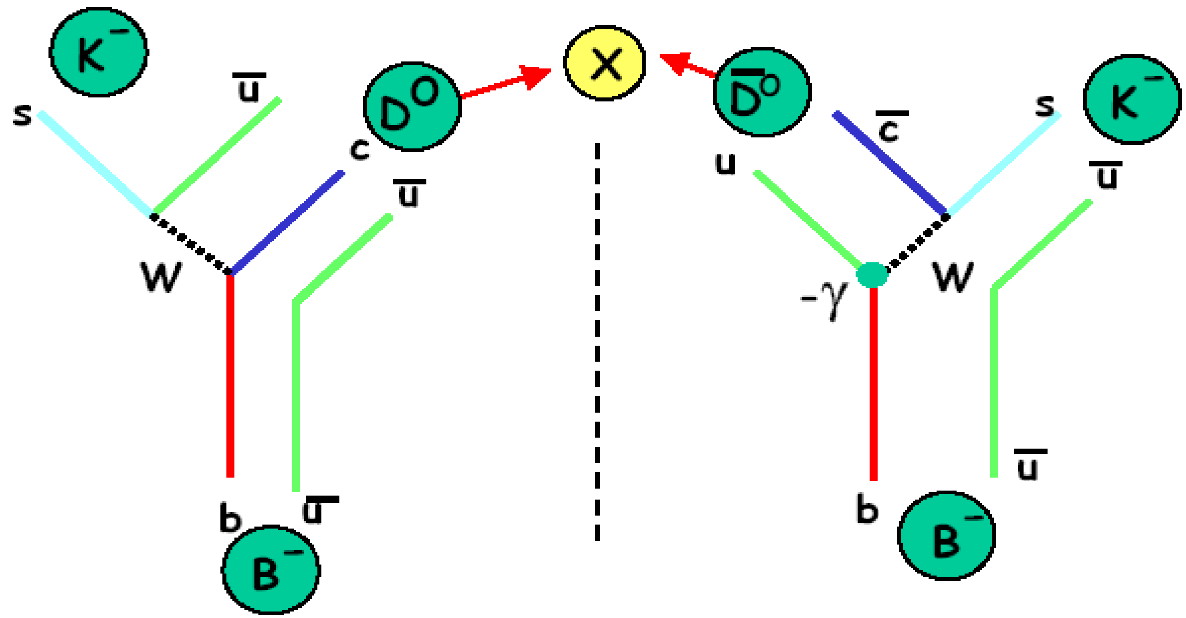
  four different flavours

- **many modes**

  $X_{CPES}=K_s\,\pi,\ K_s\,\rho,\ \pi^+\,\pi^-,\ \ldots$

  $X_{CPNES}=K^+\,\pi^-,\ K^{+*}\,\pi^-,\ \ldots$

  $K^{+*}\,K^-,\ \pi^+\,\rho^-,\ \ldots$



GLW: X=CPES
ADS: $X=K^+\pi^-$ etc.
GGSZ: Dalitz analysis of $D^0\rightarrow$ 3-body modes, for ex. $K_s\pi^+\pi^-$

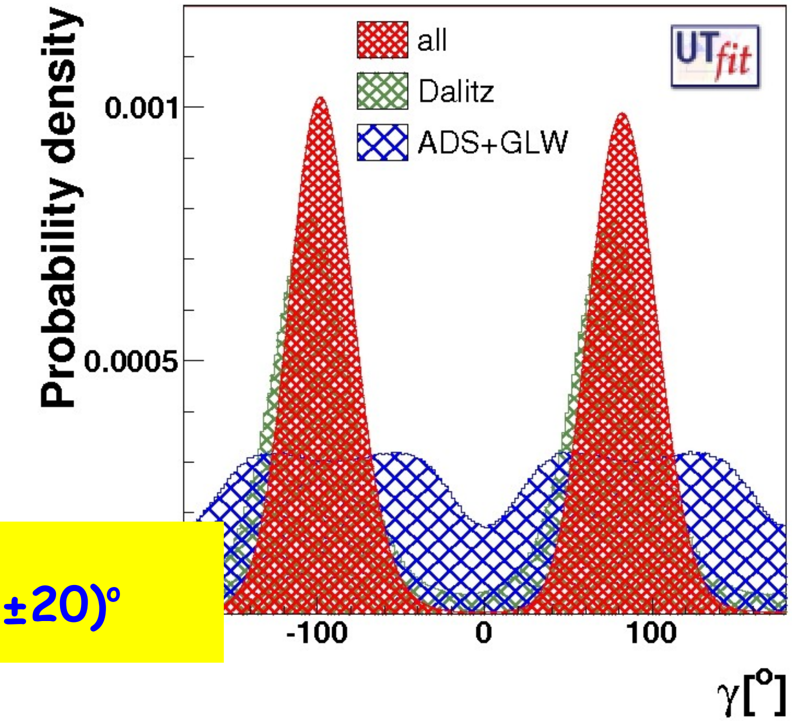
B$^\pm$: CP violation in the decay

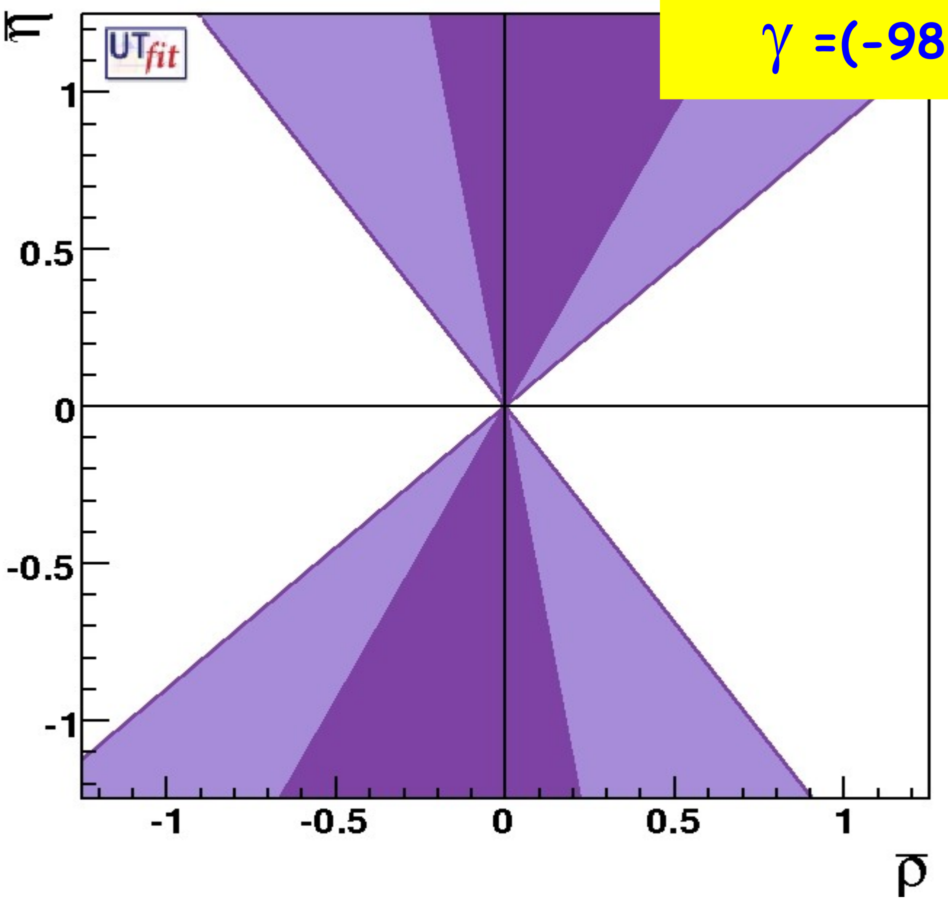
$\Rightarrow\ \gamma$

B^0 : CP violation in the interference between mixing and decay

$\Rightarrow\ \sin(2\beta+\gamma)$

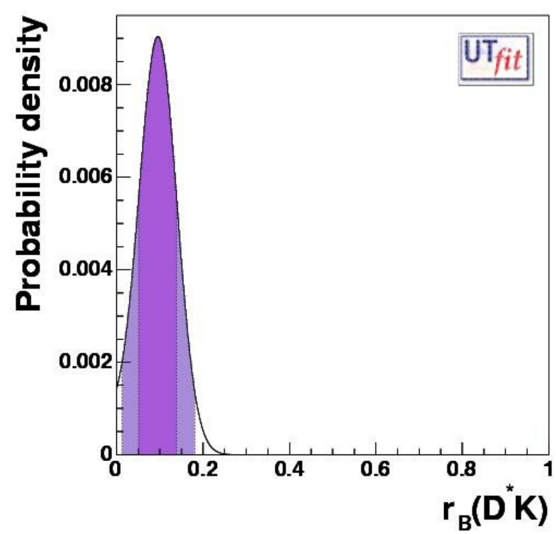
Present determination of γ

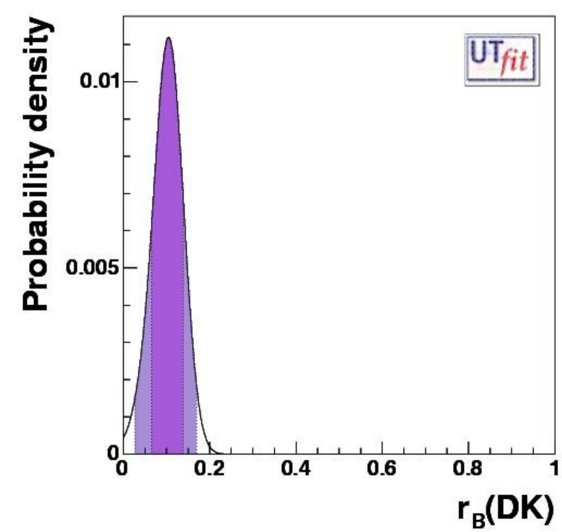




γ =(-98±20)° U (82±20)°

$$r_B(D^{(*)}K) = \left| \frac{A(B^- \rightarrow D^{(*)}K^-)}{A(B^- \rightarrow \bar{D}^{(*)}K^-)} \right|$$





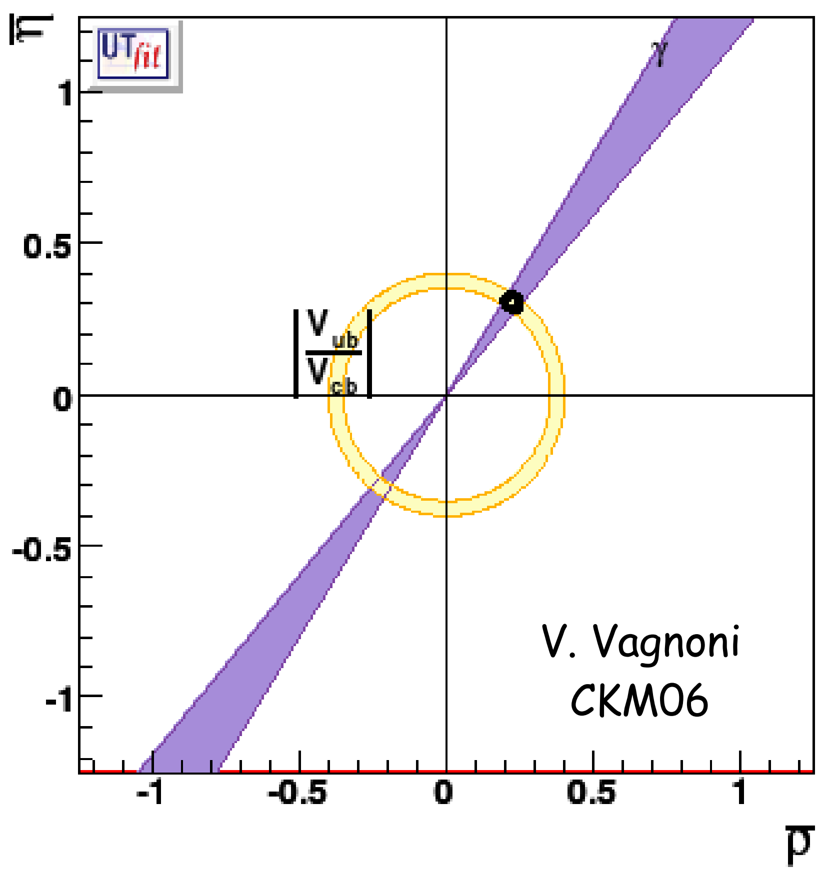
Perspectives for γ

WG2, preliminary

BF (Now) $\sim 1\ ab^{-1}$	BF(End '08) $2\ ab^{-1}$	LHCb $2\ fb^{-1}$	LHCb $10\ fb^{-1}$	SBF $50\ ab^{-1}$	ITE
30° (46%)	15° (23%)	4.6° (7%)	2.6° (4%)	2° (3%)	O(0.1%)

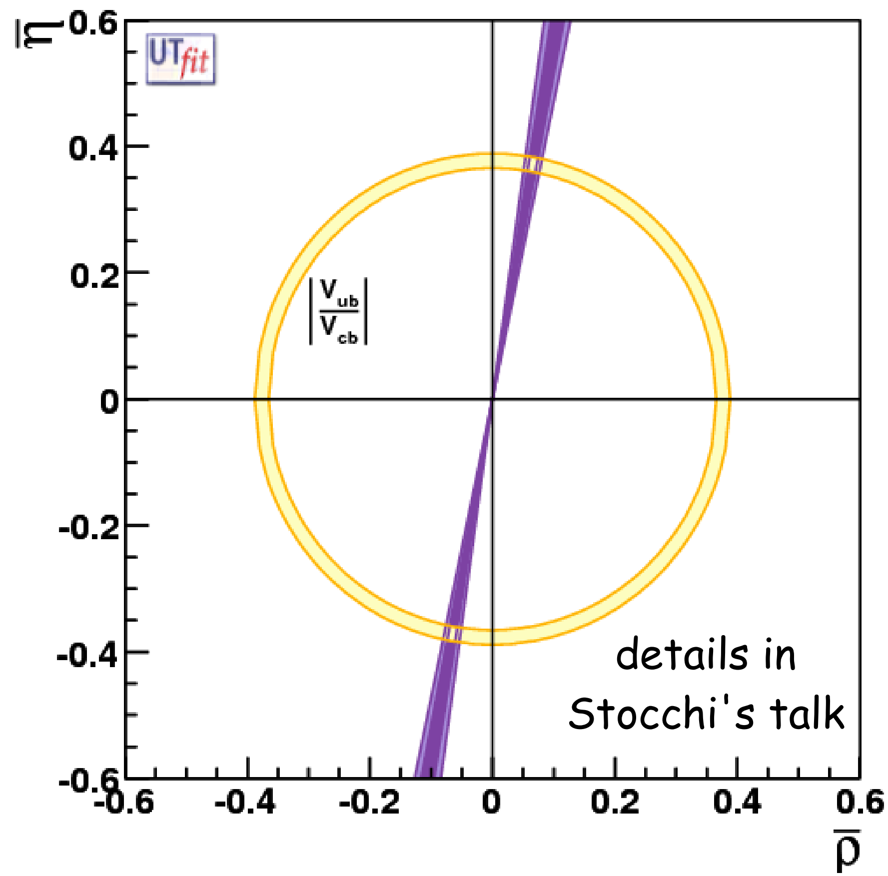
LHCb (5 years)

- GLW, ADS, GGSZ
- $B_s \to D_s K$



SuperB (5 years)

- GLW, ADS, GGSZ



α from B->ρρ/ρπ/ππ and isospin symmetry

Parametrization of the B -> ρρ/ππ amplitudes (neglecting EWP)

Gronau, London, PRL65 (1990) 3381

$$A^{+-} = -T e^{-i\alpha} + P e^{i\delta_P}$$

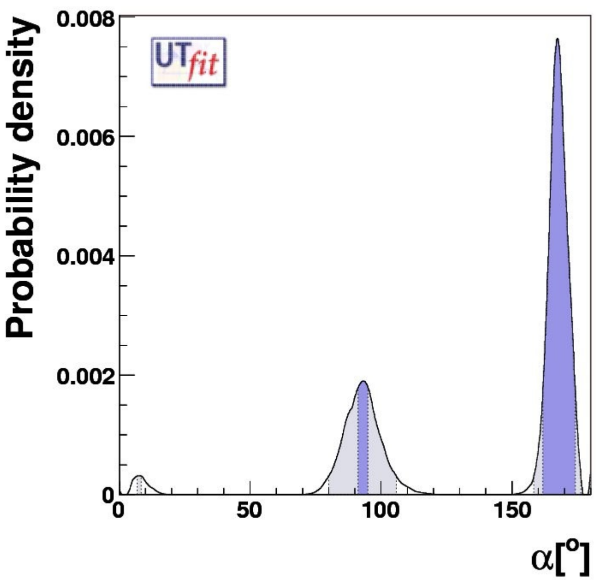
$$A^{+0} = -\frac{1}{\sqrt{2}} e^{-i\alpha}\left(T + T_c e^{i\delta_C}\right)$$

$$A^{00} = A^{+0} - \frac{1}{\sqrt{2}} A^{+-}$$

- 6 unknowns: $T, T_c, P, \delta_P, \delta_C, \alpha$
- 6 observables: $3\times BR_{ave}, C_{+-}, S_{+-}, C_{00}$

+ time-dependent Dalitz plot study of $(\rho\pi)^0$ à la Snyder-Quinn

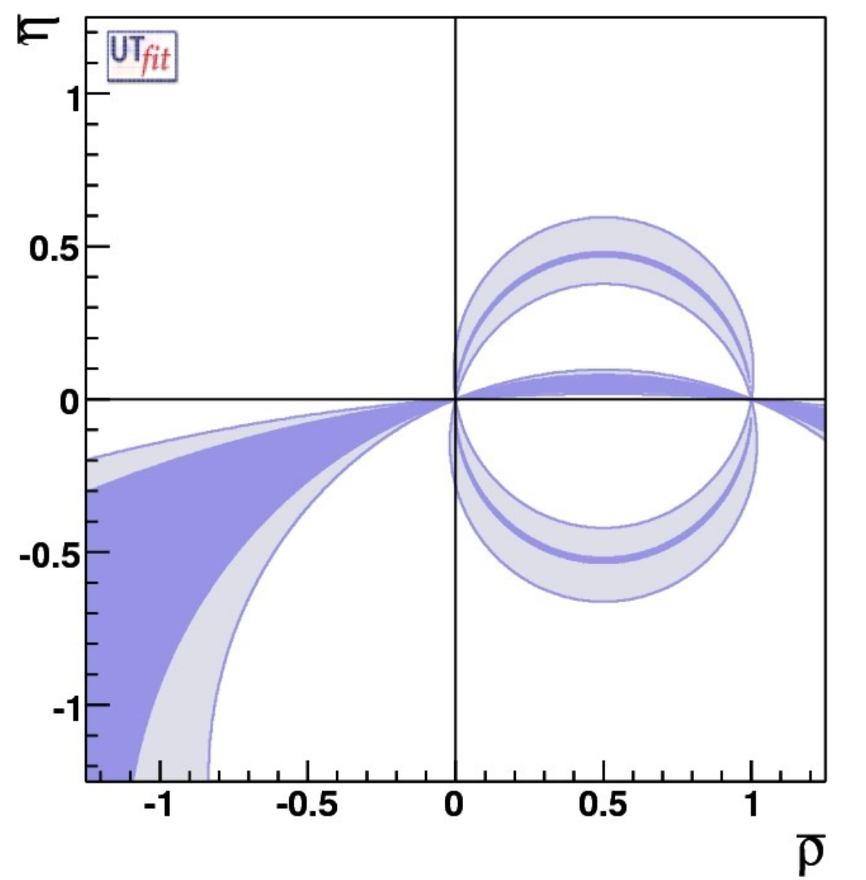
PRD48 (1993) 2139



$\alpha = [7,8]^\circ \cup$
$[80,106]^\circ \cup$
$[158,176]^\circ$ @95%

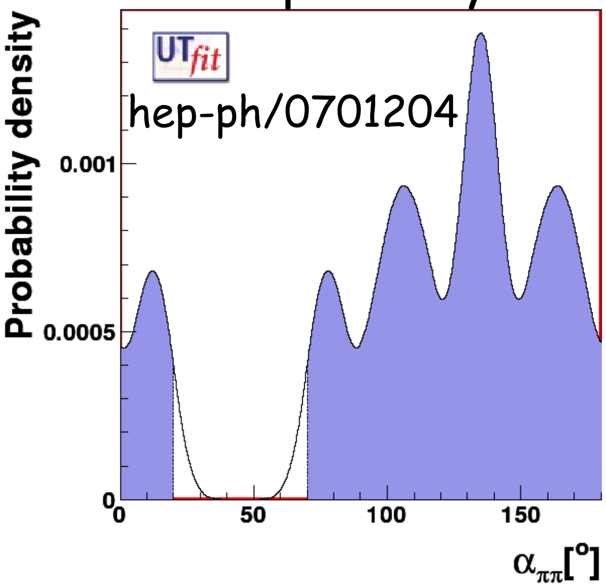
SM-like solution:

$\alpha = (92 \pm 7)^\circ$

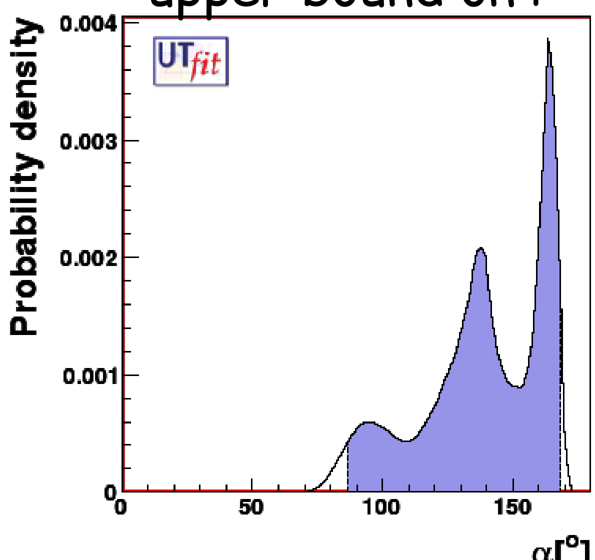


Bayesian probability

isospin analysis



isospin analysis + upper bound on P



A popular mistake: α from B->$\pi\pi$

- can CP be violated with α = 0?

  Remember that $C_{+-} \neq 0$ at > 5σ

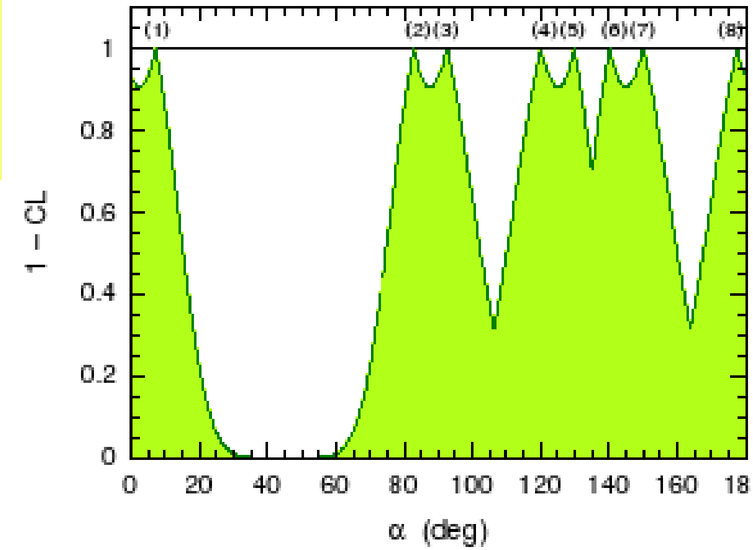
- is the isospin analysis reliable if SU(3) violation is > 3000%?

  α < 2 implies P > 30

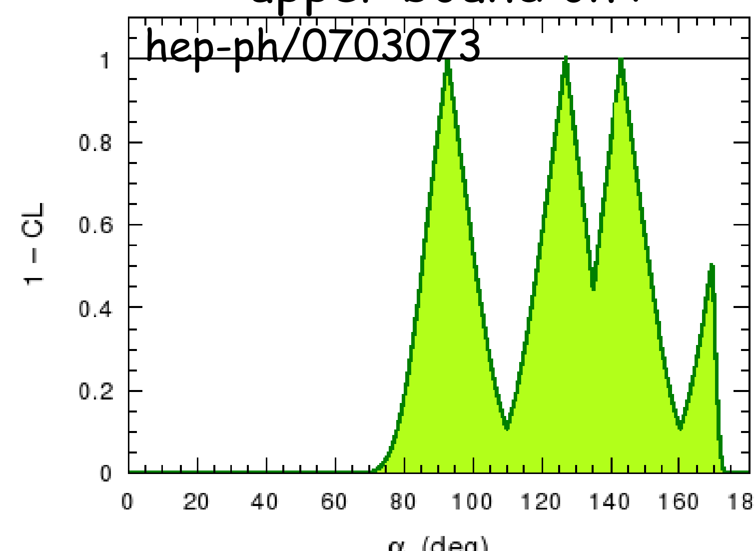
  BR(B_s->K^+K^-) requires P ~ 1 using SU(3) + reasonable breaking

Frequentist C.L.

isospin analysis



isospin analysis + upper bound on P



Perspectives for α

WG2, preliminary

BF (Now) $\sim 1\ ab^{-1}$	BF(End '08) $2\ ab^{-1}$	LHCb $2\ fb^{-1}$	LHCb $10\ fb^{-1}$	SBF $50\ ab^{-1}$	ITE
$10°$ (11%)	$7°$ (8%)	$8.1°$ (9%)	$4.6°$ (5%)	$1.5°$ (1.6%)	O(few %)

- Theoretical error from "isospin breaking"
  - ElectroWeak Penguins

    dominant LxL EWP's calculable: $\Delta\alpha \sim$ few degrees
  - η-η'-π^0 mixing Gronau, Zupan, hep-ph/0502139

    model-dependent estimate: $\Delta\alpha \sim 1$ degree
  - $(m_d-m_u)/\Lambda_{QCD}$ and α_e effects in matrix elements

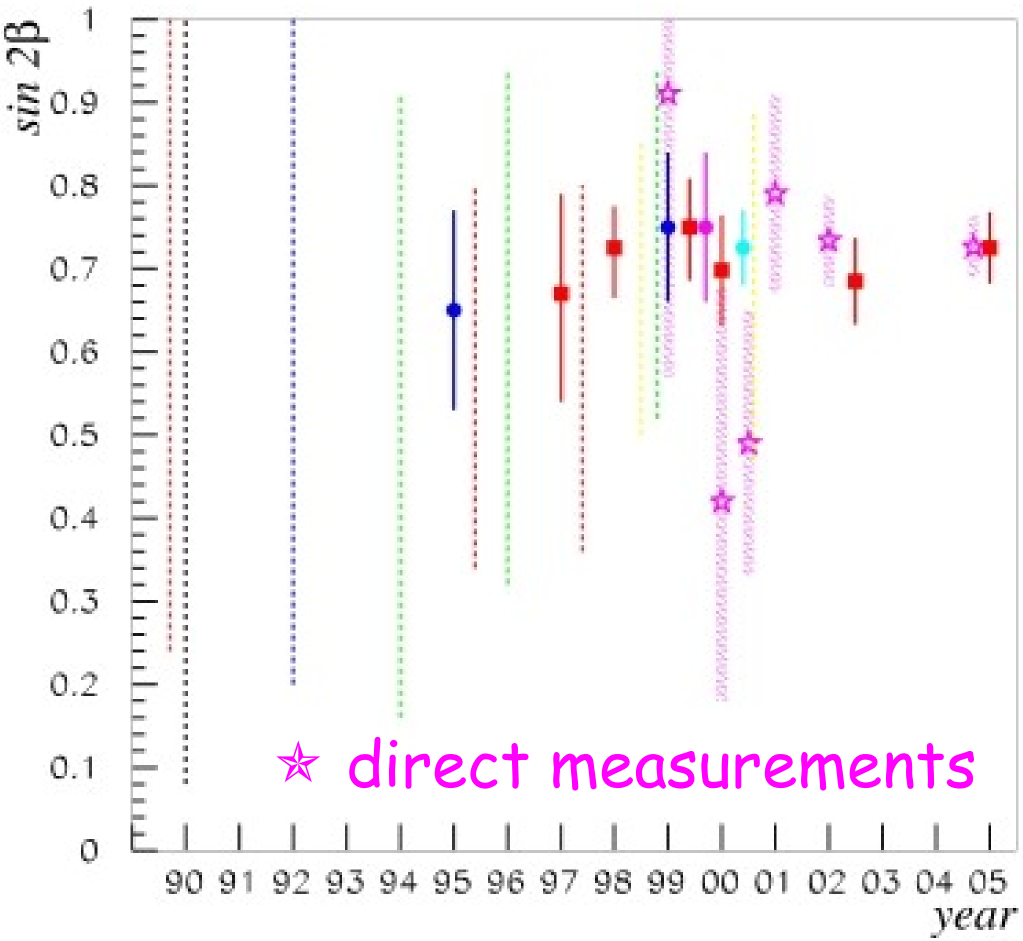
    order-of-magnitude estimate: $\Delta\alpha$ small
- Sensitivity to New Physics
  - potentially sensitive to NP in penguins

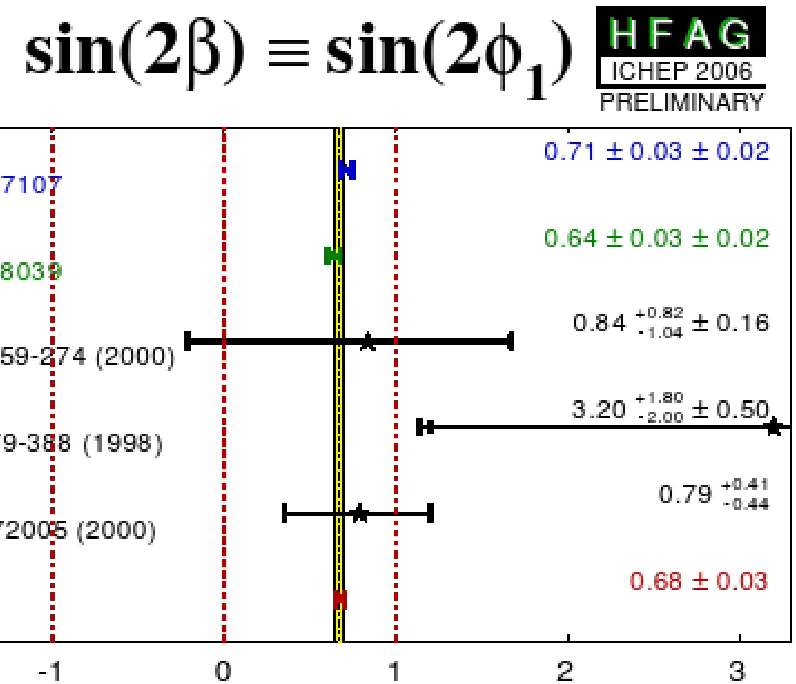
    isospin analysis sensitive to EWP-like contributions only

    QCD-penguin-like NP just redefine hadronic amplitudes

β from B->J/ψ K$^{(*)}$

$$a_{CP}^{J/\psi K_S}(t) = -\mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}}{A}\right)\sin(\Delta m_B t) = \sin 2\beta \times \sin(\Delta m_B t)$$





Predictions existed since early 90s

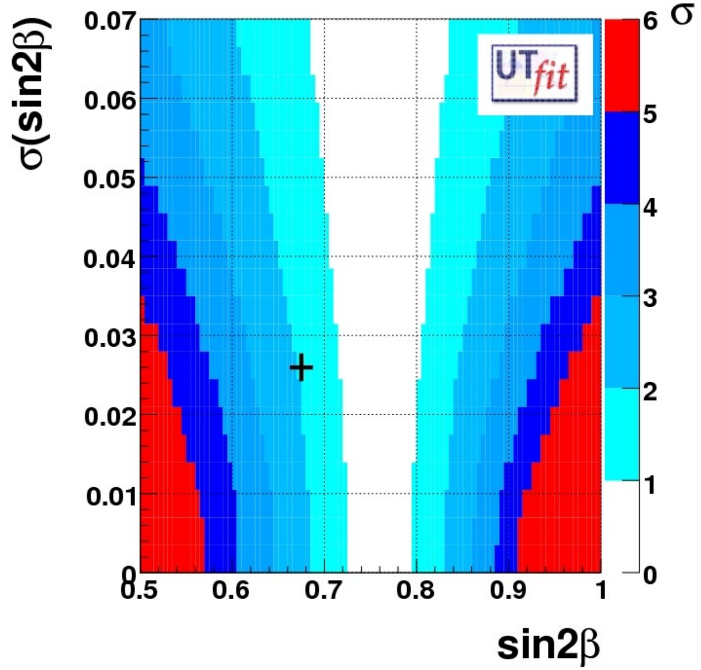
$\sin 2\beta = 0.65 \pm 0.12$

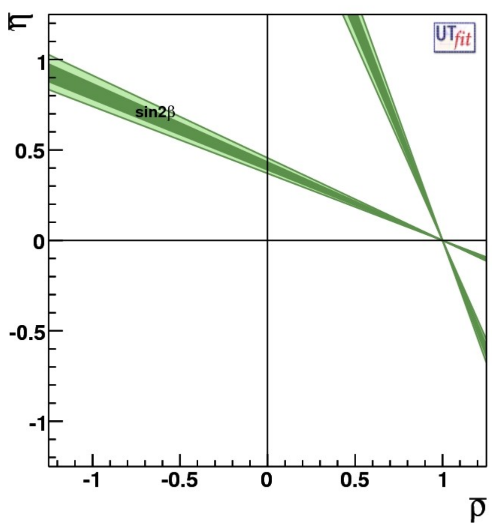
MC et al., hep-ph/9501265

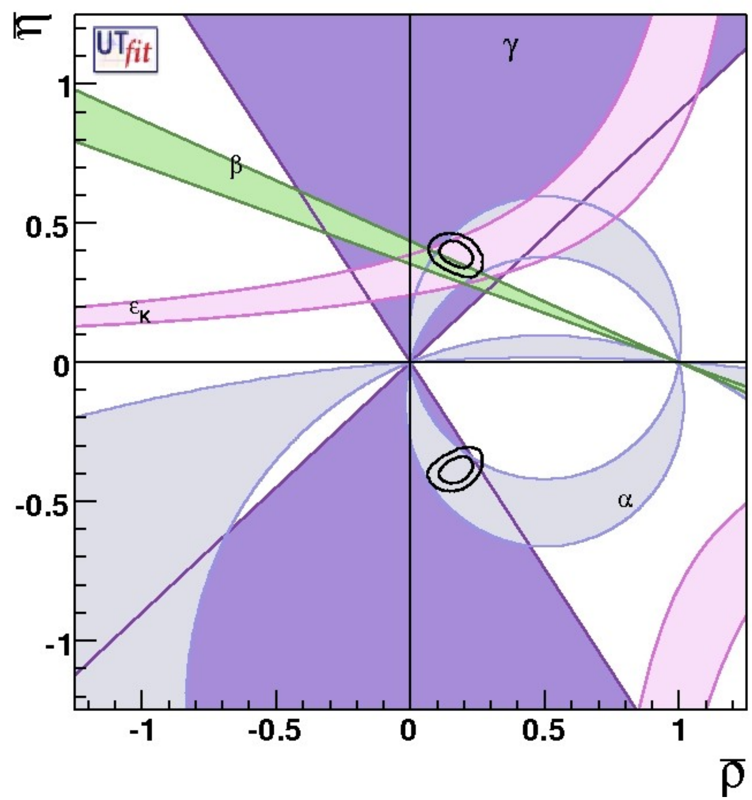
current determination of 2β

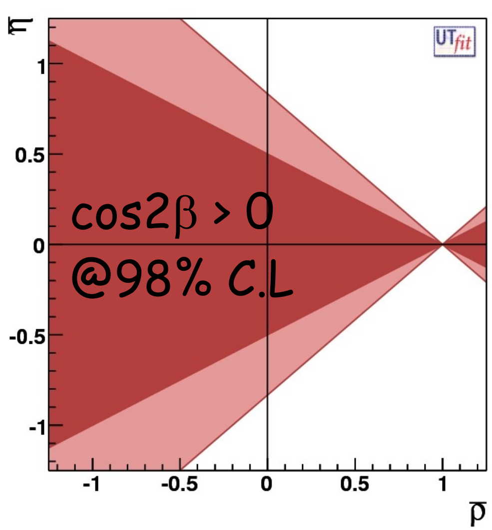
$\sin 2\beta^{exp} = 0.68 \pm 0.03$
$\sin 2\beta^{fit} = 0.76 \pm 0.04$

Tension!

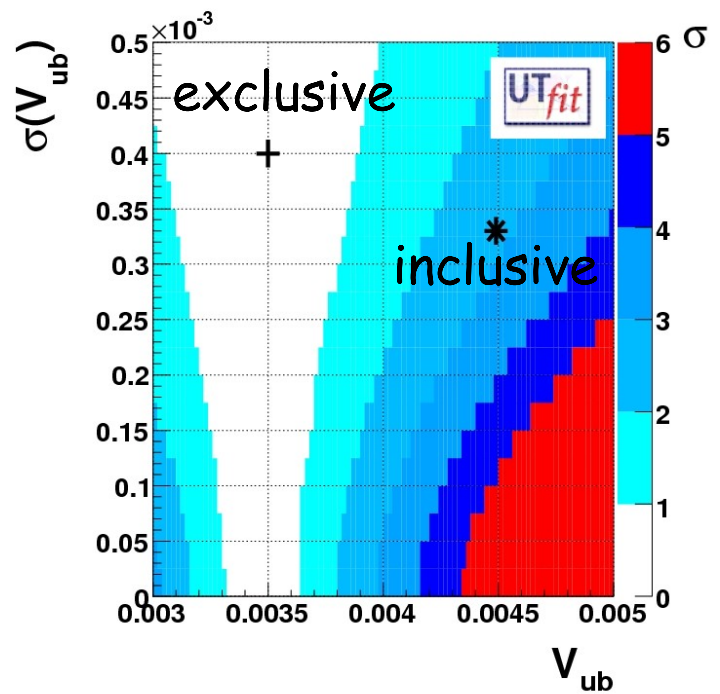








likely due to V_{ub} inclusive: no NP at work



How precious is the golden mode?

$$A(B \to J/\psi\, K^0) = \underbrace{V_{cb}^* V_{cs}}_{\lambda^2}\, \underbrace{(E_2+P_2)}_{T} - \underbrace{V_{ub}^* V_{us}}_{\lambda^4} \underbrace{(P_2^{GIM}-P_2)}_{P}$$

- the "polluting" amplitude $P = P_2^{GIM} - P_2$ is a pure u-penguin

naïve estimate: $V_{cb}^* V_{cs} P / V_{ub}^* V_{us} T \sim \lambda^2 \alpha(m_b)/4\pi \sim 10^{-3}$

confirmed by factorization Boos, Mannel, Reuter, hep-ph/0403085 Li, Mishima, hep-ph/0610120

Data-driven estimate getting a little help from a friend:

$$A(B \to J/\psi\, \pi^0) = \underbrace{V_{cb}^* V_{cd}}_{\lambda^3}\, \underbrace{(E_2+P_2)}_{T} - \underbrace{V_{ub}^* V_{ud}}_{\lambda^3} \underbrace{(P_2^{GIM}-P_2-\cancel{EA_2})}_{P}$$

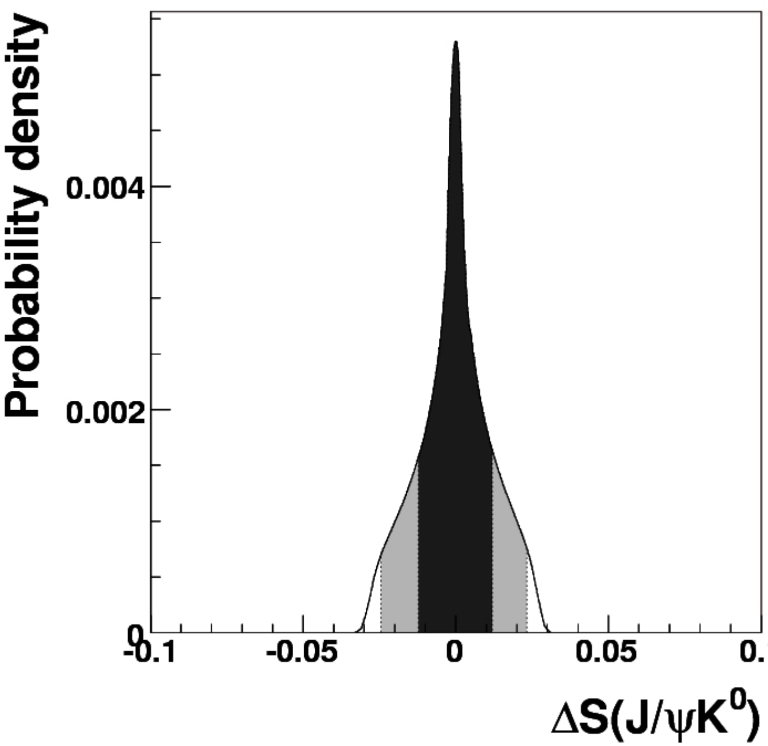
Strategy: CPS, hep-ph/0507290

1. fix the *range* of $|P|$ from $J/\psi\, \pi^0$
2. use it to evaluate ΔS in $J/\psi\, K^0$

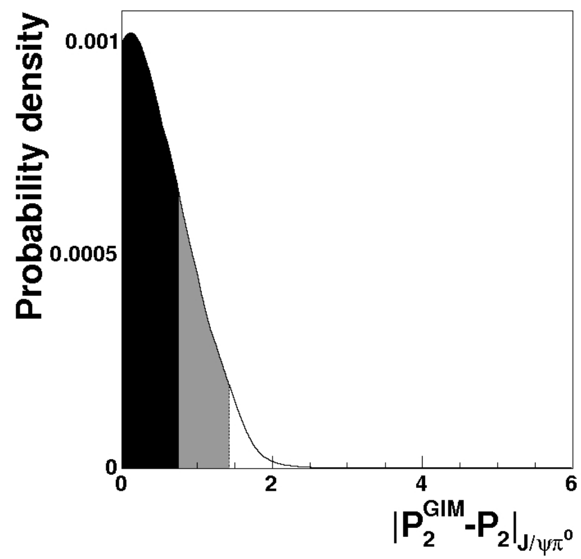
range instead of value: weaker use of SU(3)

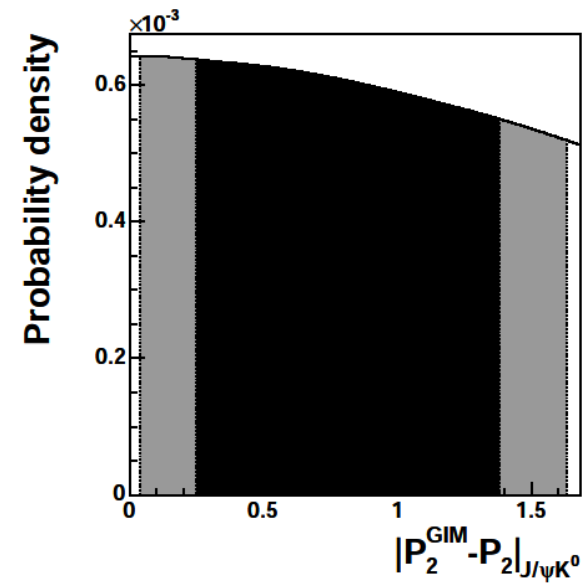
Using this info in the $B^0 \to J/\psi K^0$ fit :

$\mathcal{BR}^{th}[10^{-4}]$	8.61 ± 0.35	$\mathcal{BR}^{exp}[10^{-4}]$	8.63 ± 0.35
C_{CP}^{th}	0.00 ± 0.015	C_{CP}^{exp}	0.001 ± 0.031
S_{CP}^{out}	0.759 ± 0.040	S_{CP}^{in}	0.759 ± 0.037
$\lvert E_2 - P_2 \rvert$	1.465 ± 0.035		



The input from $B^0 \to J/\psi\, \pi^0$ i.e. $|P| < 1.7$ (99% probability) is crucial





$$\Delta S(J/\psi\, K^0) = \sin 2\beta_{eff} - \sin 2\beta$$
$$= 0.000 \pm 0.012$$

Perspectives for sin2β

WG2, preliminary

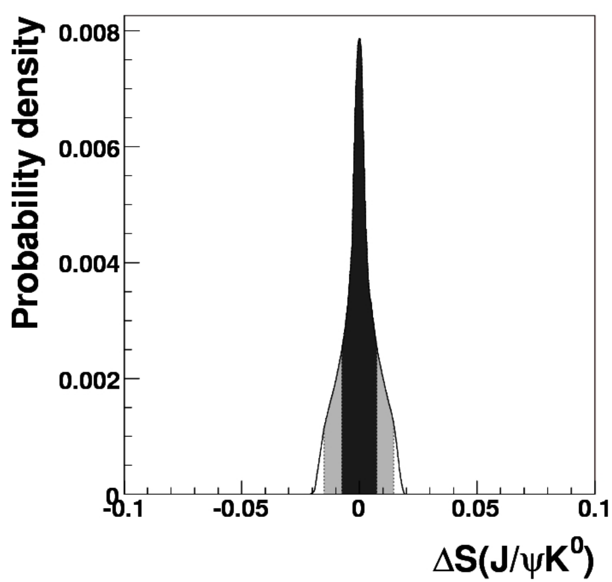
^{a} : statistical error only

BF (Now) $\sim 1\ ab^{-1}$	BF(End '08) $2\ ab^{-1}$	LHCb $2\ fb^{-1}$	LHCb $10\ fb^{-1}$	SBF $50\ ab^{-1}$	ITE
0.026 (4%)	0.023 (3.3%)	0.017 (2.4%) ^{a}	0.008 (1%) ^{a}	0.013 (2%)	$\lesssim 1\%$

- the measurement is systematic-dominated at SBF
- theoretical error is likely not to be a problem

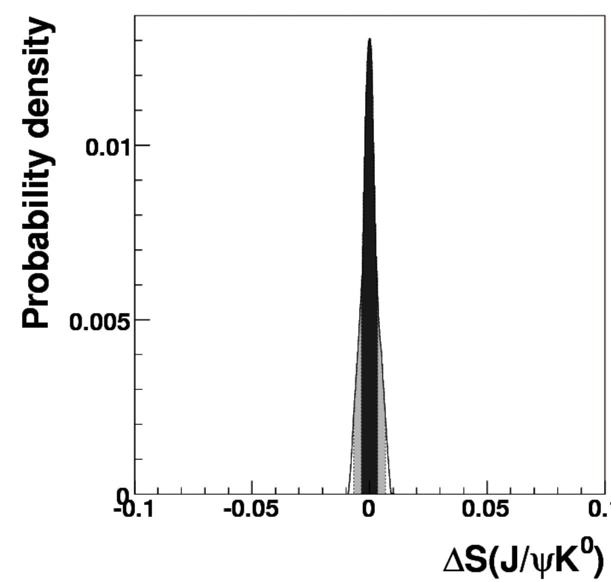
scaling the B->J/ψ π^0 analysis:

2 ab^{-1}: $\Delta S = 0.000 \pm 0.007$



$\sigma^{sys}(S) > 0.005\text{-}0.01$ irreducible (and largely correlated) systematic error

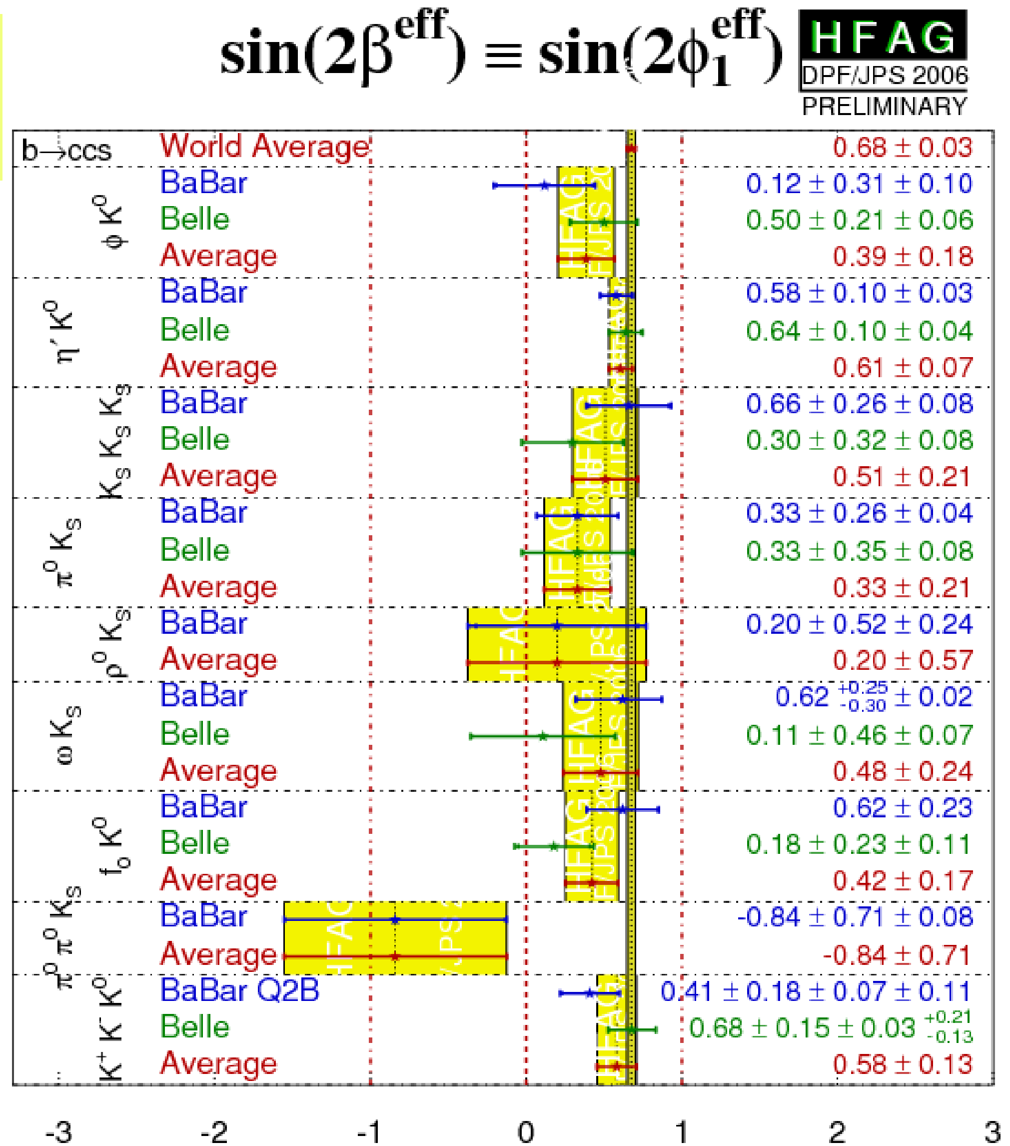
30 ab^{-1}: $\Delta S = 0.000 \pm 0.003$



β from b->q$\bar{q}$s and NP

- decays dominated by a single b->s penguin amplitude
- $a_{CP}(t)$ measures sin2β in the SM up to DCS corrections
- NP corrections to penguins change the expectation sin2β -> sin2β^{eff}

Best place to look for NP in 2-body non-leptonic decays



$$\mathcal{A}(B^0 \to \phi\, K^0) = V_{cs}\, V_{cb}^* \times \boldsymbol{P}_{1+2}(c) + V_{us}\, V_{ub}^* \times \boldsymbol{P}_{1+2}(u)$$

$$\lambda^2 \qquad\qquad \lambda^4$$

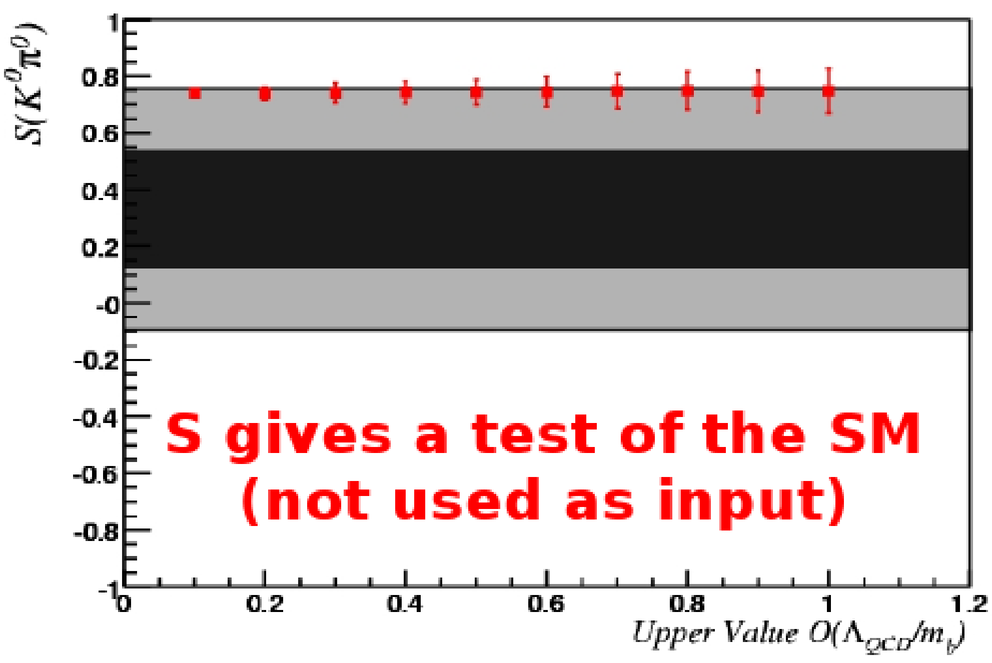
$$\mathcal{A}(B^0 \to K^0\, \pi^0) = V_{cs}\, V_{cb}^* \times \boldsymbol{P}_1(c) + V_{us}\, V_{ub}^* \times \{\boldsymbol{E}_2 + \boldsymbol{P}_1(u)\}$$

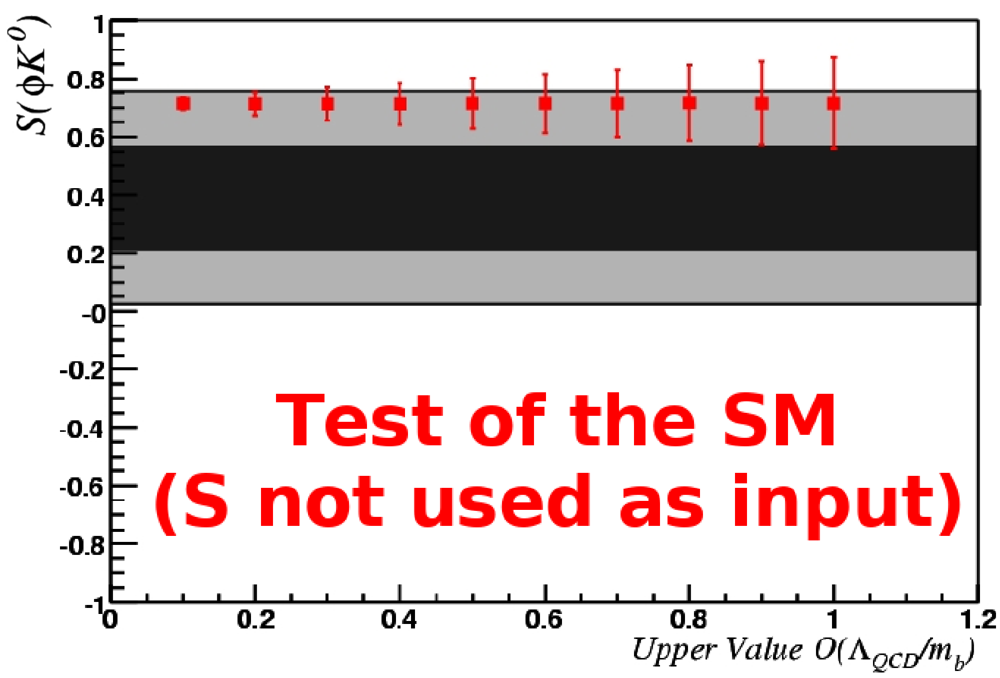
Contributions from doubly-Cabibbo-suppressed SM amplitudes can fake a NP signal

"Data-driven" method to put bounds on th. uncertainites:

M.Pierini, CKM '06

- color-allowed emission diagram E_1 computed in factorization
- leading P term fitted using BR_{ave} and direct CP asymmetries
- other hadronic amplitudes varied between 0 and E_1





$\Delta S(K^0\pi^0) < \sim 0.1$

$\Delta S(\phi K^0) < \sim 0.2$

Using for instance QCD factorization to compute the amplitudes, ΔS can be evaluated

- the ratio P_u/P_c is roughly constant and universal: $\Delta S \sim 0.02$
- the ratio E_2/P_c is responsible for the different ΔS
- the size and sign of the corrections are dictated by the size of E_2/P_c and relative sign between the two ratios

WG2, preliminary

Mode	ΔS_f (Theory)	ΔS_f [Range]	Mode	ΔS_f (Theory)	ΔS_f [Range]
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$[+0.03, 0.13]$	$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.01]$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$	$[+0.00, 0.03]$	ϕK_S	$0.02^{+0.01}_{-0.01}$	$[+0.01, 0.05]$
ηK_S	$0.10^{+0.11}_{-0.07}$	$[-0.76, 0.27]$	ωK_S	$0.13^{+0.08}_{-0.08}$	$[+0.02, 0.21]$

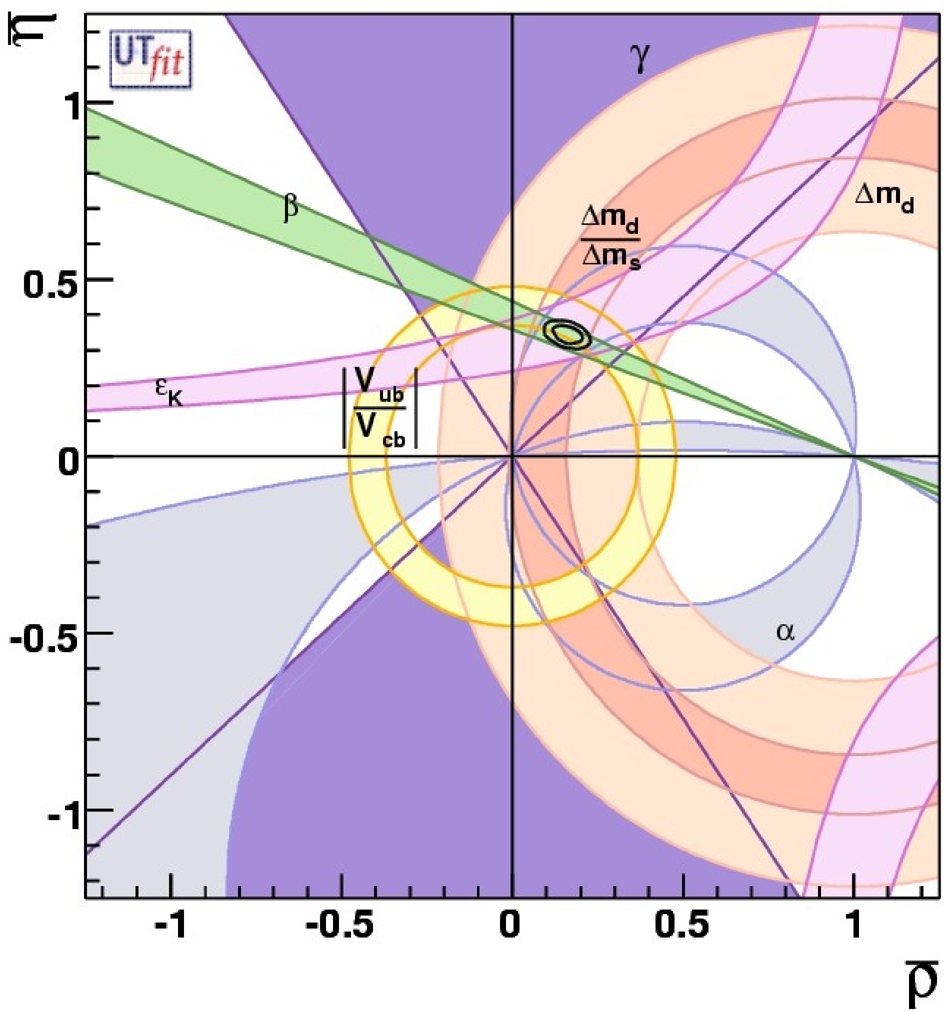
but: factorization of c-penguins is still debated

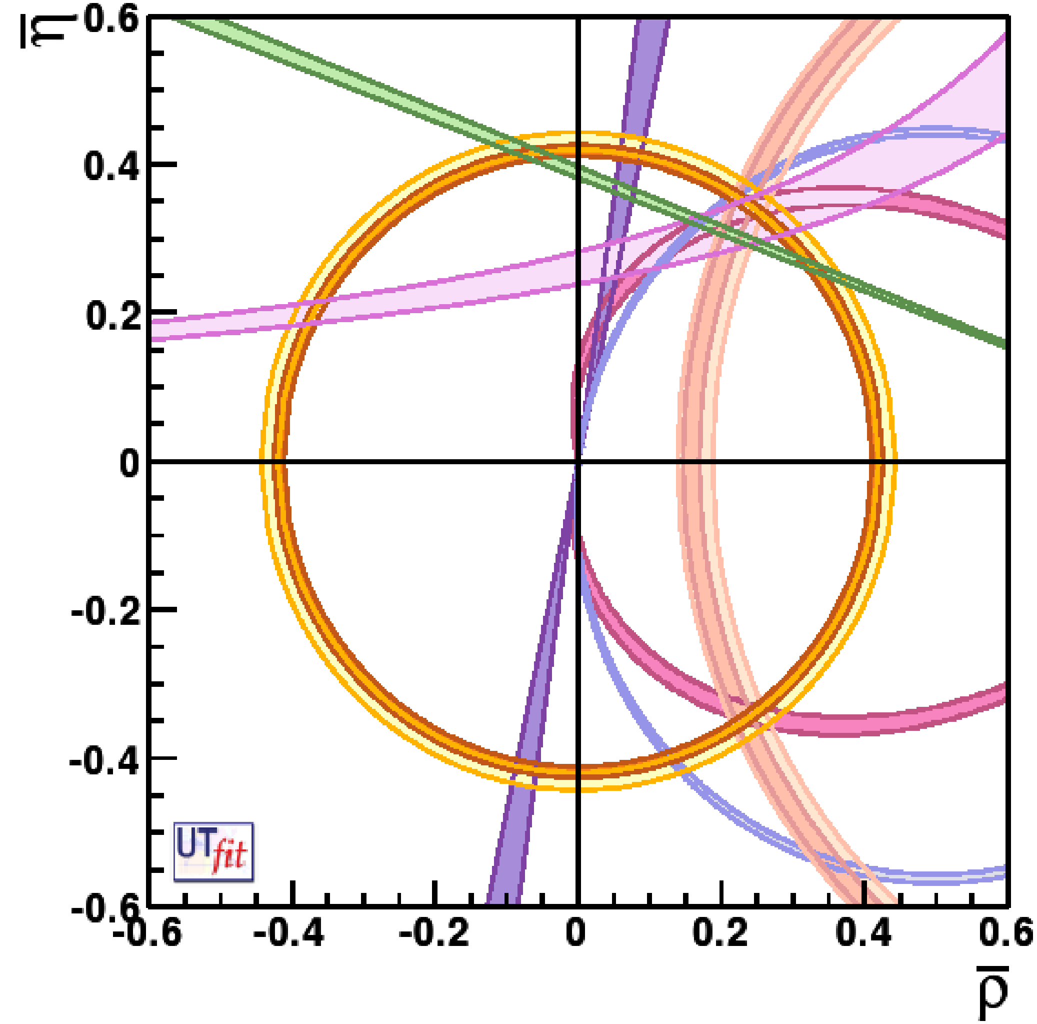
power-suppressed terms can be important

Sides and angles consistent within present errors

It could be much different with SBF accuracy

see Stocchi's talk





Neutral meson mixing

Mixing amplitudes with generic NP contributions:

$$A_{B_q} = A_{B_q}^{SM} e^{2i\beta_q} + A_{B_q}^{NP} e^{2i(\beta_q + \phi_q^{NP})} = C_{B_q} e^{2i(\beta_q + \phi_{B_q})} A_{B_q}^{SM}$$

Observables:

$$\Delta m_q = 2 C_{B_q} |A_{B_q}^{SM}|$$

$$S^{B_d \to J/\psi K_S} = \sin 2(\beta_d + \phi_{B_d})$$

$$a_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_{B_q} \right)$$

$$S^{B_s \to \phi K_S} = \sin 2(\beta_s + \phi_{B_s})$$

$$\Delta \Gamma_q = -\Delta m_q \mathrm{Re}\left(\Gamma_{12}^q / A_{B_q} \right)$$

$$a_{CH}^{\mathrm{dimuon}} = f(a_{SL}^d, a_{SL}^s)$$

Standard Model: $C_{Bq}=1$, $\phi_{Bq}=0$

CKM fits determine ρ, η, C_{Bq}, ϕ_{Bq} simultaneously

UTfit, hep-ph/0509219; hep-ph/0605213

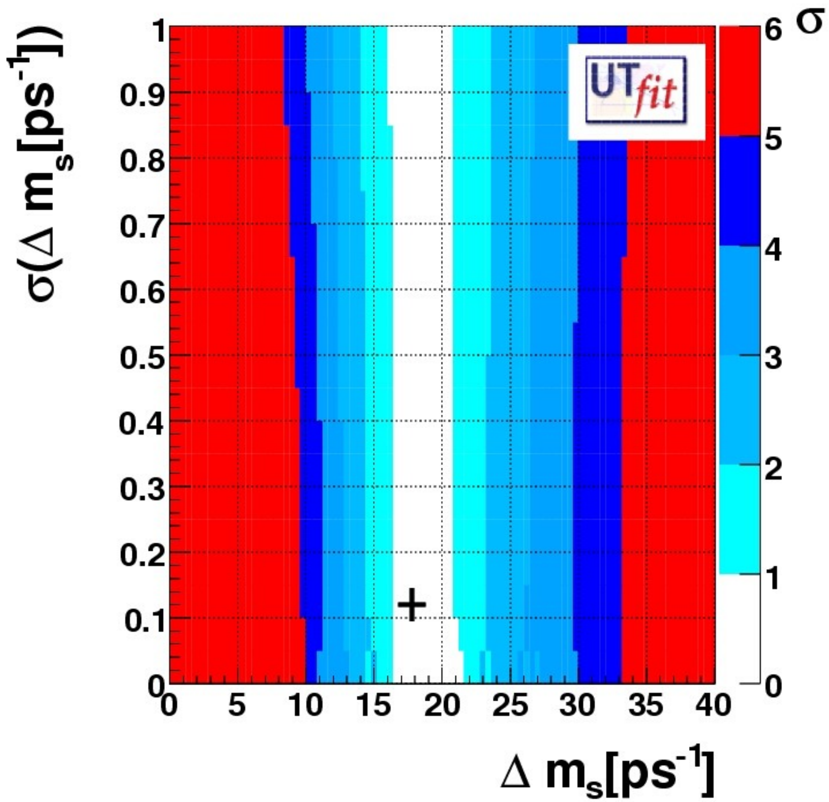
Information on the moduli

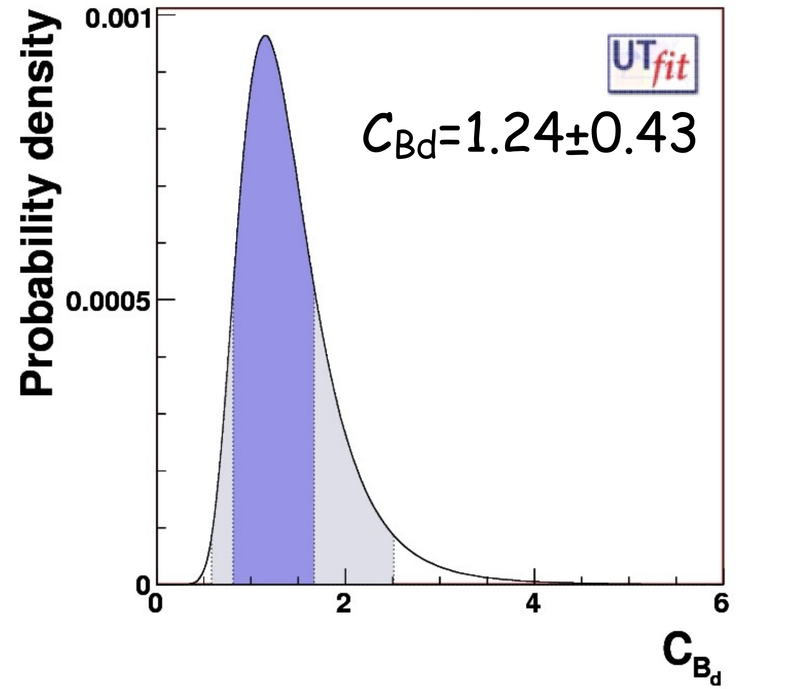
- B_d mixing:

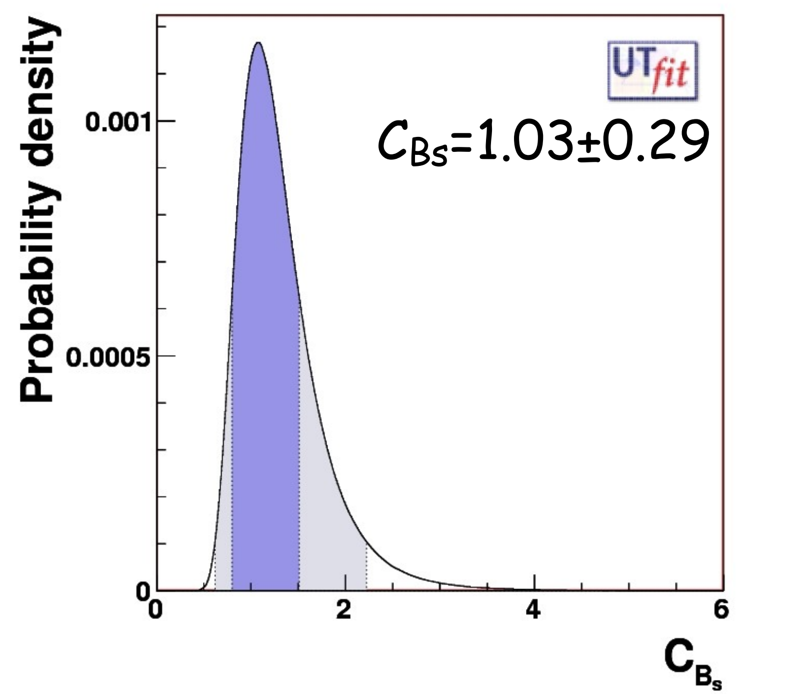
  $\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$

- B_s mixing:

  $\Delta m_s = 17.77 \pm 0.01 \pm 0.07\ ps^{-1}$







Accessing the B_s mixing phase

Recent ϕ_{Bs}-sensitive measurements from the Tevatron

$a_{CH}^{dimuon} = (-9.2 \pm 4.4 \pm 3.2) \times 10^{-3}$ measured by D0

$\Delta\Gamma_s = (0.47^{+0.19}_{-0.24} \pm 0.01)\ \mathrm{ps}^{-1}$ measured by CDF

$A_{SL}^{s} = (24.5 \pm 19.3 \pm 3.5) \times 10^{-3}$ measured by D0

+ the t-dependent angular analysis of $B_s \to J/\psi\, \phi$ by D0 resulting in a 3D likelihood for Γ_s, $\Delta\Gamma_s$ and ϕ_{Bs}

For comparison the SM expections at NLO are:

MC et al, hep-ph/0308029; Lenz,Nierste, hep-ph/0612167

$\Delta\Gamma_s/\Gamma_s = (11 \pm 4) \times 10^{-2}$ $A^{s}_{SL} = (2.3 \pm 0.5) \times 10^{-5}$

Spectacular measurements of Bs observables and particularly of ϕ_{Bs} expected from LHCb

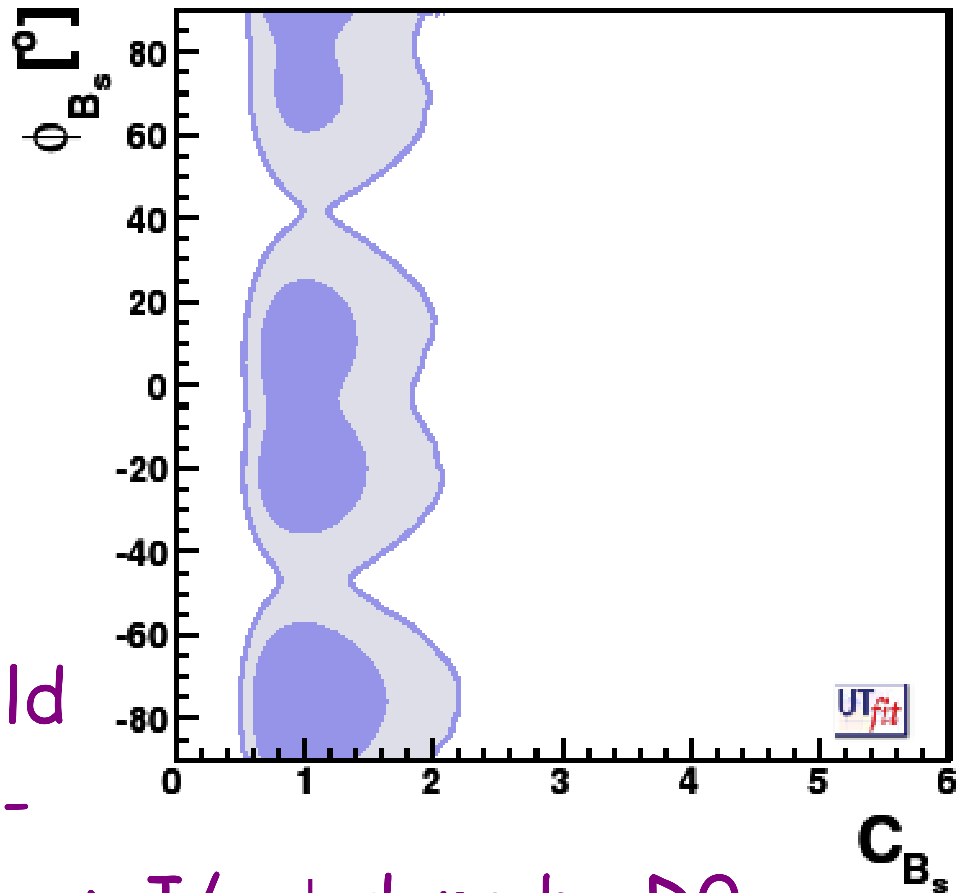
Information on the phases

- B_d mixing:

  $\phi_{Bd}=(-3\pm2)^\circ$

- B_s mixing:

  $\phi_{Bs}=(-75\pm14)^\circ \cup (-19\pm11)^\circ \cup (9\pm10)^\circ \cup (102\pm16)^\circ$



The result retains the the 4-fold ambiguity of the untagged time-dependent angular analysis of $B_s \to J/\psi\,\phi$ done by D0

$$(\phi_{Bs}, \cos\delta_{1,2}) \leftrightarrow (-\phi_{Bs}, -\cos\delta_{1,2}),\ (\phi_{Bs}, \Delta\Gamma_s) \leftrightarrow (\pi+\phi_{Bs}, -\Delta\Gamma_s)$$

only weakly lifted by A_{CH} and A^s_{SL} which prefer $\phi_{Bs} < 0$

Factorization and SU(3) give opposite signs for $\cos\delta_{1,2}$

MSSM + generic soft SUSY-breaking terms

A useful tool: the mass-insertion approximation

SuperCKM basis + perturbative smass diagonalization

- expansion parameters: $(\delta_{ij}^{q})_{AB} \equiv \dfrac{(M_{ij}^{2})_{AB}^{q}}{\widetilde{m}^{2}}$

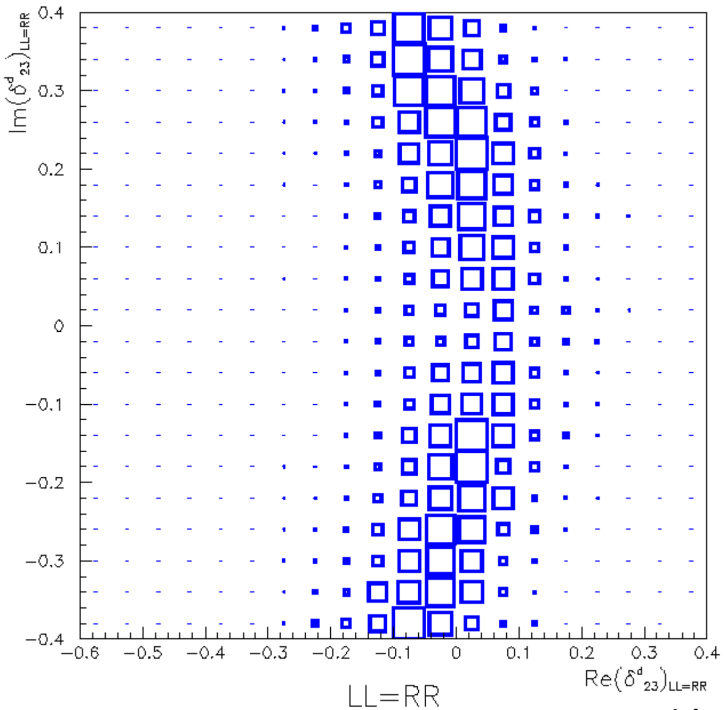
All flavour-changing NP effects in the squark propagators

$$(\tilde{q}_i)_A \; - - - \overset{(\delta_{ij}^{q})_{AB}}{\times} - - - \; (\tilde{q}_j)_B$$

$$q=\{u,d\},\ (A,B)=\{L,R\}$$
$$(i,j)=\{1,2,3\}$$

FCNC and CP violation impose model-independent bounds on the δ's

NB: only dominant gluino contributions are considered



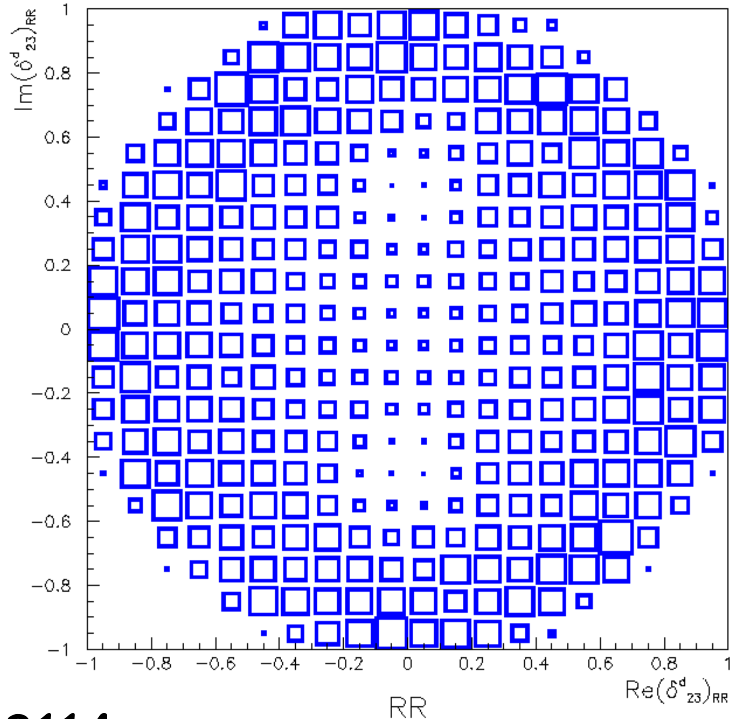
<- before ->

Tevatron B_s measurements

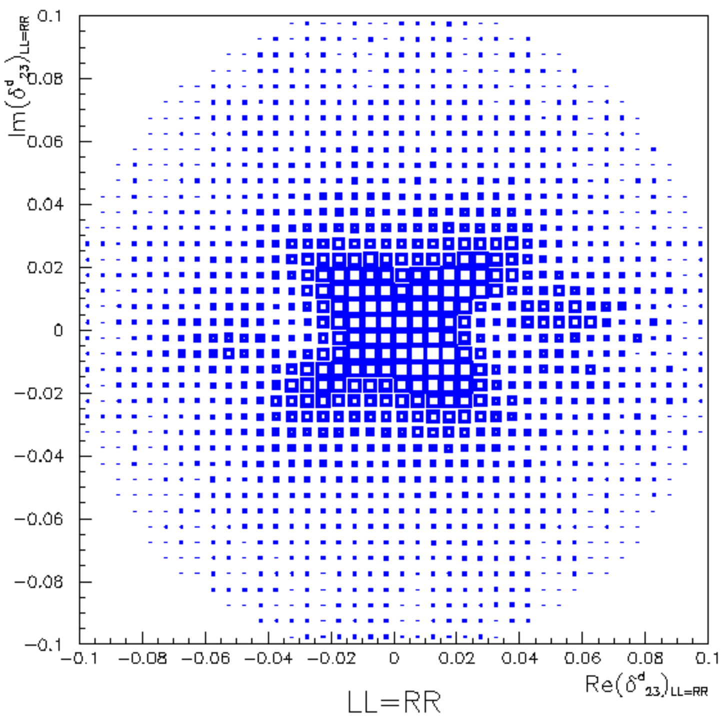
$|\delta|$ unbounded

$m_{gl}=m_{sq}=-\mu=350$ GeV

$\tan\beta=3$



MC, Silvestrini, hep-ph/0603114



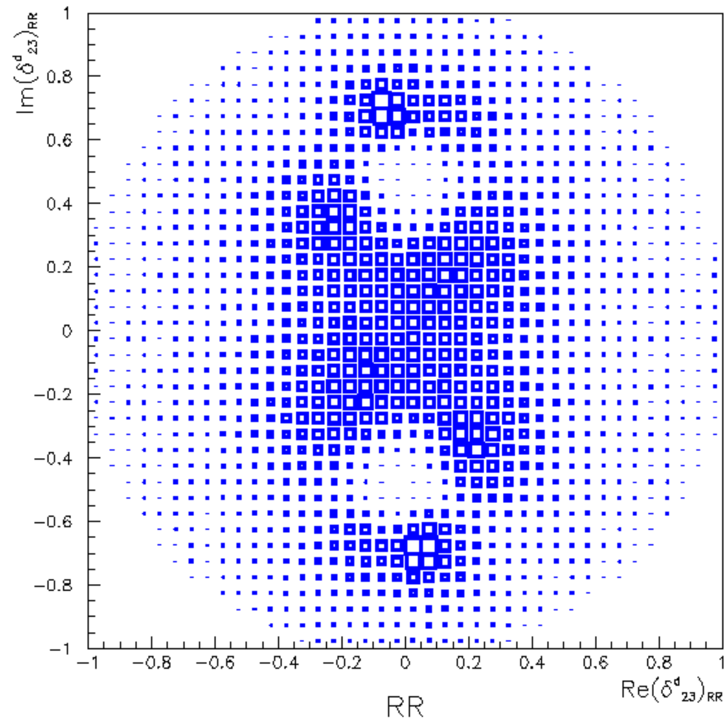
<- after ->

Tevatron B_s measurements

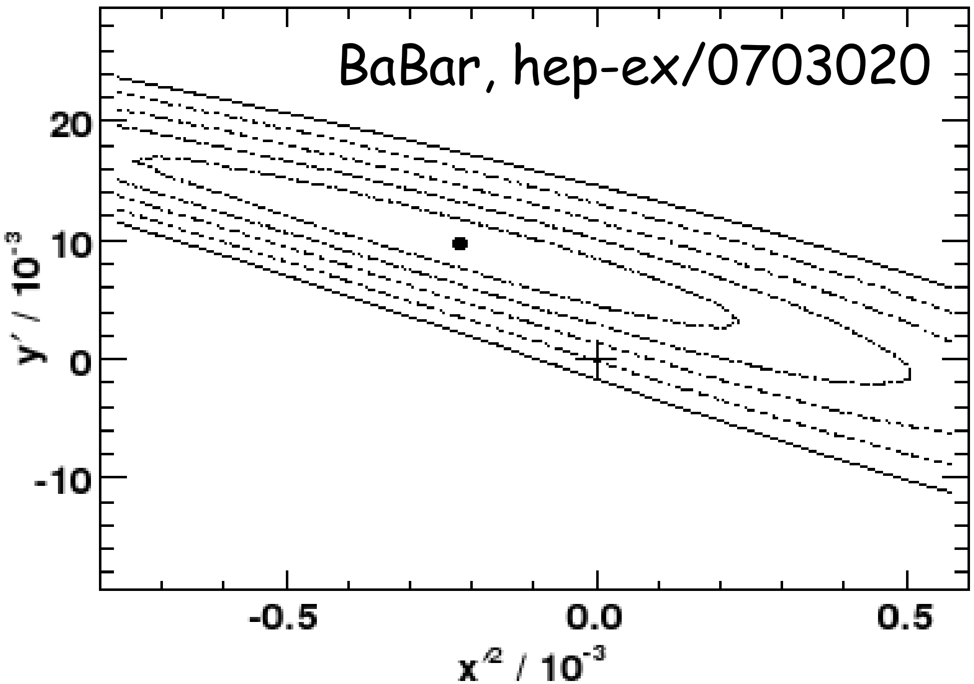
$\left\|(\delta^d_{23})_{LL}\right\|$	$\left\|(\delta^d_{23})_{RR}\right\|$
$2\cdot10^{-1}$	$7\cdot10^{-1}$

$\left\|(\delta^d_{23})_{LL=RR}\right\|$	$\left\|(\delta^d_{23})_{LR,RL}\right\|$
$5\cdot10^{-2}$	$5\cdot10^{-3}$

WG2, preliminary



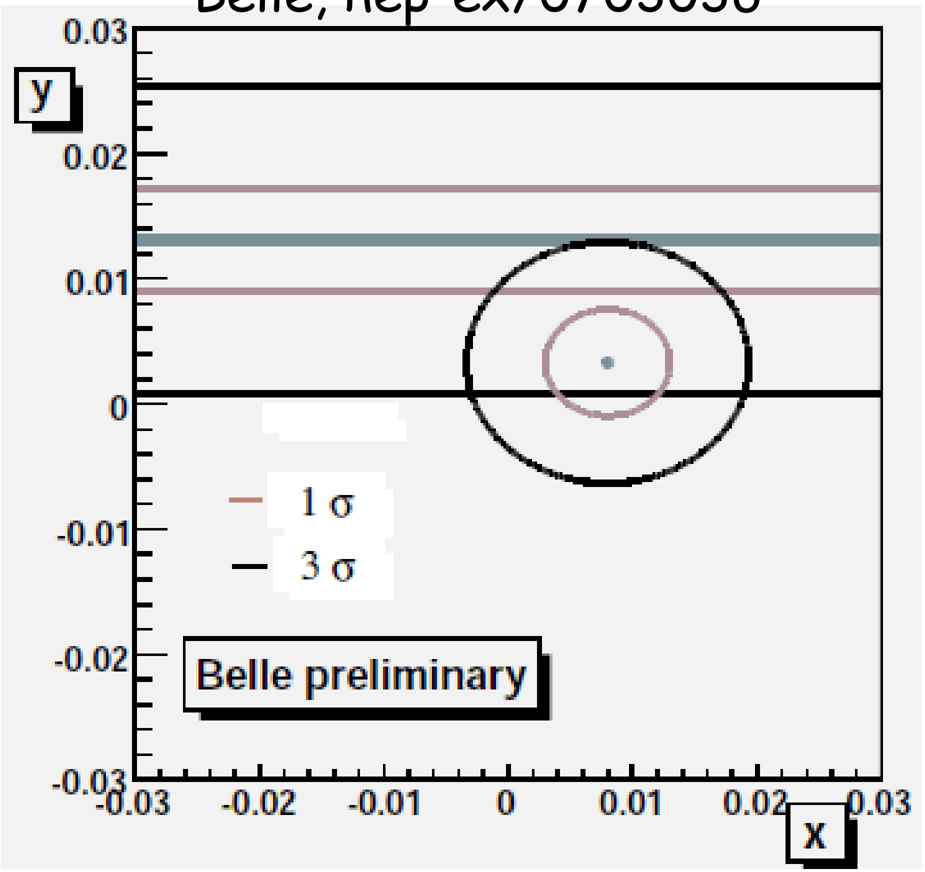
Breaking news: evidence of D-$\bar{D}$ mixing

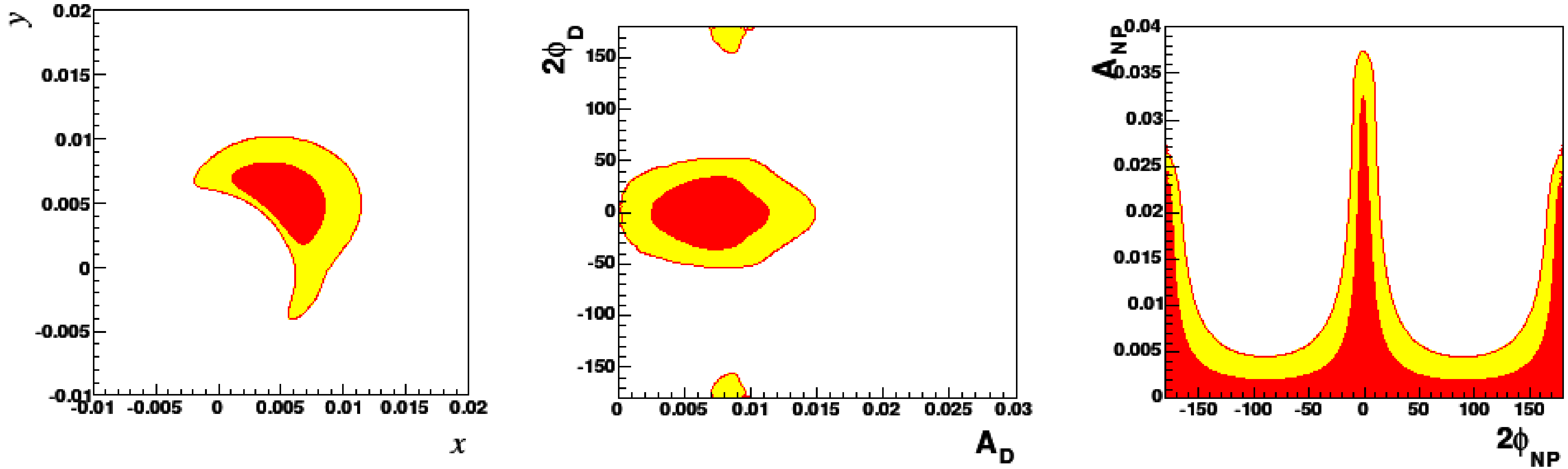


$$
\begin{aligned}
y'_\pm &= (1 \pm A_m)(y' \cos 2\phi_D \mp x' \sin 2\phi_D)\,, \\
x'^2_\pm &= (1 \pm 2A_m)(x' \cos 2\phi_D \pm y' \sin 2\phi_D)^2\,, \\
y_{CP} &= y \cos 2\phi_D - A_m x \sin 2\phi_D\,, \\
A_\Gamma &= A_m y \cos 2\phi_D - x \sin 2\phi_D\,,
\end{aligned}
$$

Parameter	Value
x'^2_+	$(-0.24 \pm 0.43 \pm 0.30) \cdot 10^{-3}$
x'^2_-	$(-0.20 \pm 0.41 \pm 0.29) \cdot 10^{-3}$
y'_+	$(9.8 \pm 6.4 \pm 4.5) \cdot 10^{-3}$
y'_-	$(9.6 \pm 6.1 \pm 4.3) \cdot 10^{-3}$
x	$(8.0 \pm 3.4) \cdot 10^{-3}$
y	$(3.3 \pm 2.8) \cdot 10^{-3}$
y_{CP}	$(13.1 \pm 4.1) \cdot 10^{-3}$
A_Γ	$(0.1 \pm 3.4) \cdot 10^{-3}$

Belle, hep-ex/0703036



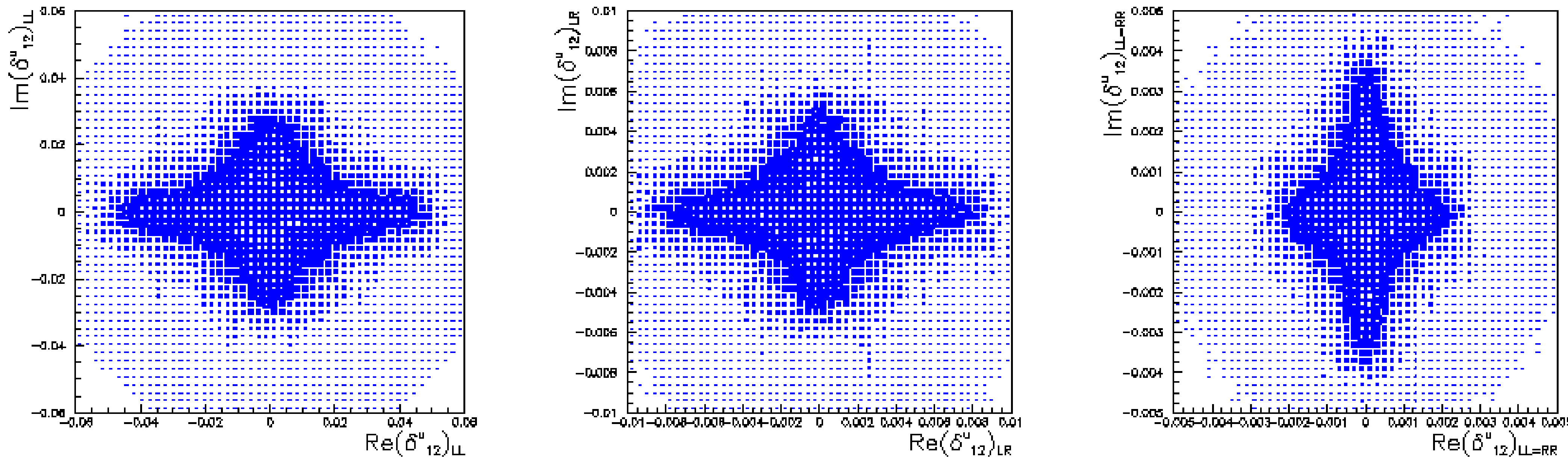


MC at al, hep-ph/0703204
Nir, hep-ph/0703235

Bounds on MSSM MI's improved by an order of magnitude

$m_{\tilde{q}}$	$m_{\tilde{g}}$	$\lvert(\delta^u_{12})_{LL,RR}\rvert$	$\lvert(\delta^u_{12})_{LR,RL}\rvert$	$\lvert(\delta^u_{12})_{LL=RR}\rvert$
350	350	0.032	0.0056	0.0027

Quark-squark alignment ruled out for squark masses within LHC reach



Conclusions (i)

γ is poorly known (error ~ 20% + ambiguity) but will improve with statistics. No systematic and th. limitations up to SBF. Very well measured at LHCb

Error on α is 10% if ambiguities are eliminated with external information. Measurement eventually limited by isospin breaking effects. Sensitive to EWP-like NP

β known at 5%. Systematically limited at ~10 ab^{-1}. Th. error under control in b->c$\bar{c}$s, limiting factor for NP searches in b->s penguin dominated decays

Conclusions (ii)

NP contributions to the B_d mixing amplitude are quite constrained from B-factory data

Missing information on B_s physics starts coming from the Tevatron. Modulus of the amplitude is already strongly constrained. First information on the phase start to put some non-trivial bound

Evidence of D-$\bar{D}$ mixing constrains NP in the up sector. SUSY models with quark-squark alignment are no longer viable unless m_{sq} > 2 TeV

T H A N K S
TO
the WG2 subgroup conveners

angles: M. Bona, A. Soni,
K. Trabelsi, G. Wilkinson

b->s: F. Muheim

mixing: V. Lubicz, J. van Hunen

and to all the contributors
(even the virtual ones...)