CP VIOLATION

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- Introduction
- CP Violation in $\Delta F=2$ processes
  - Standard model predictions
  - Constraints on New Physics
- Conclusions and Outlook

http://www.utfit.org

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

Two accidental symmetries of the SM are crucial for our discussion:

1) Absence of tree-level flavour changing neutral currents, GIM suppression of FCNC @ the loop level

2) No CP violation @ tree level

$\Rightarrow$ Flavour physics extremely sensitive to NP!!

The CP violation mechanism of the SM is very peculiar

- CP symmetry is explicitly broken by the Yukawa couplings

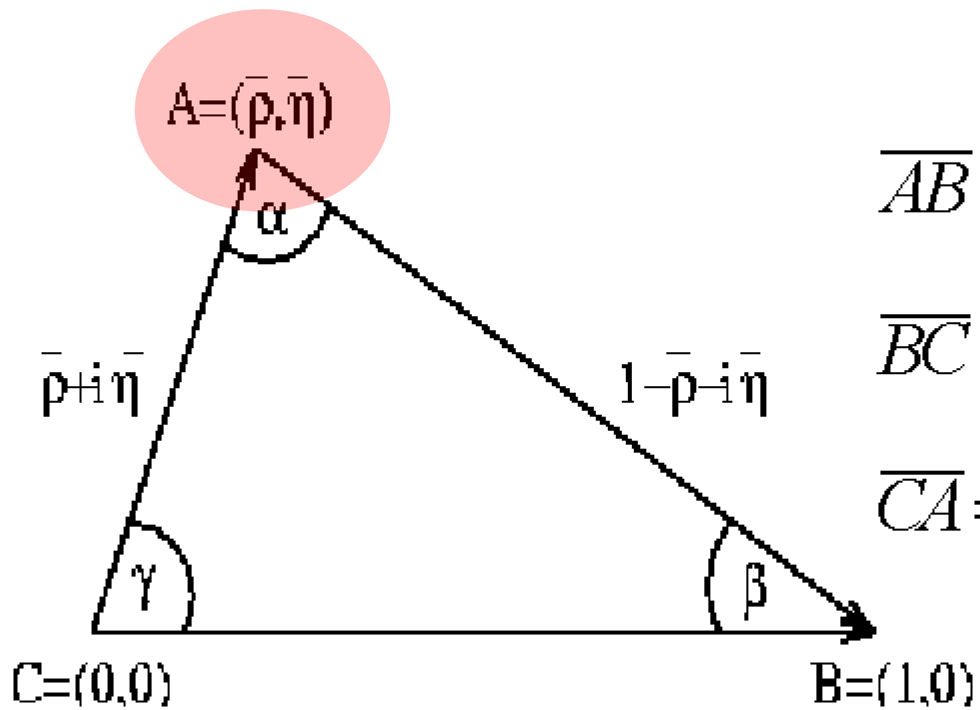
- CP is not an approximate symmetry of the model. CP violation is suppressed by mixing angles, but the phase is of O(1)

- A single source of CP violation in the weak interactions of quarks

- Three-generations unitarity: CP violation from the measurement of CP conserving observables

All these features, if experimentally confirmed, provide strong constraints on New Physics

CP physics ⇔ $\not{CP}$ physics



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

$$\overline{BC} = 1$$

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

Triangle

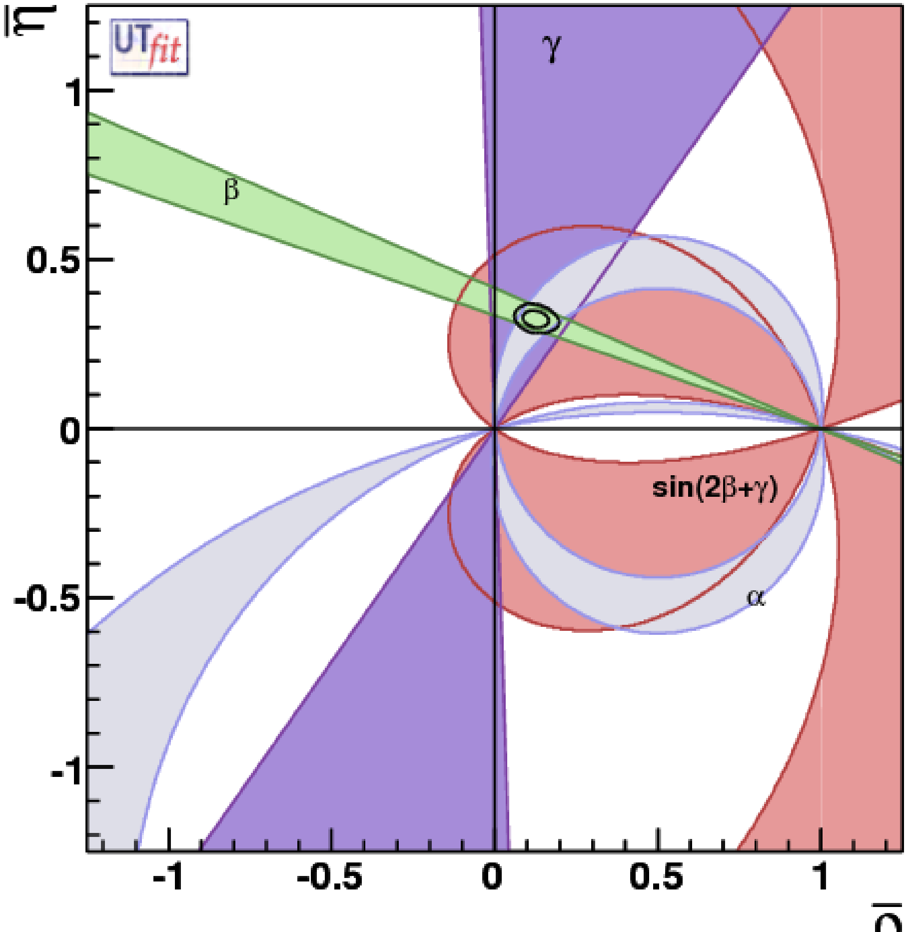
sides ↔ angles

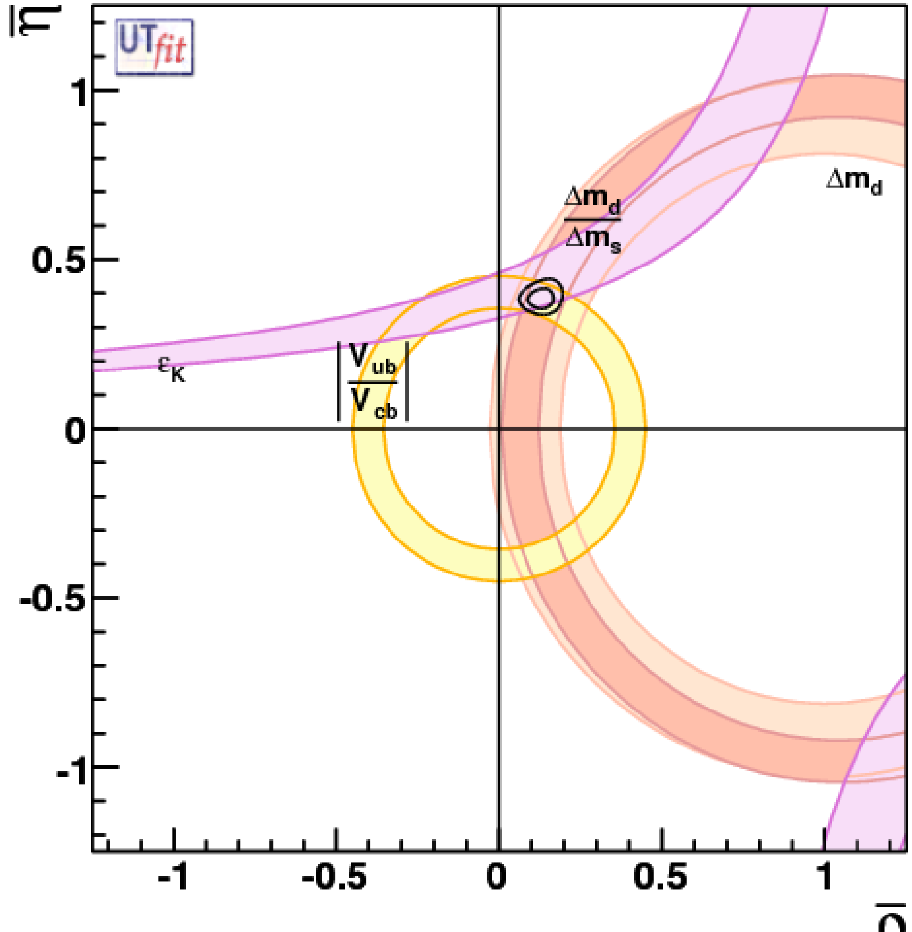
$|VV^*| \leftrightarrow \alpha, \beta, \gamma$

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

- CP violation ∝ the Jarlskog invariant $J = \mathrm{Im}\ V_{ij}V_{kl}V_{il}^*V_{kj}^*$

ANGLES vs NON-ANGLES





$\bar{\rho} = 0.126 \pm 0.028$ $\bar{\rho} = 0.131 \pm 0.028$

$\bar{\eta} = 0.324 \pm 0.017$ $\bar{\eta} = 0.387 \pm 0.021$

CPV IN KAON MIXING: ε_K

$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi \right)$$

- Aim at reaching the % level for SM error
  - M_{12}^K: $C_6 \langle Q_6 \rangle + \Sigma_i C_8^i \langle Q_8^i \rangle + \ldots$
    - C_6: NNLO in progress, 3.3% enhancement from η_{ct} Brod, Gorbahn '10
    - $\langle Q_6 \rangle$: $B_K = 0.731 \pm 0.036$ UTfit average
    - long-distance: estimate using Ch.p.t. Buras, Guadagnoli, Isidori '10
  - $\xi = \mathrm{Im}A_0/\mathrm{Re}A_0$:
    - estimate using ε'/ε few percent decrease Buras, Guadagnoli '08

ε_K: SM vs experiment

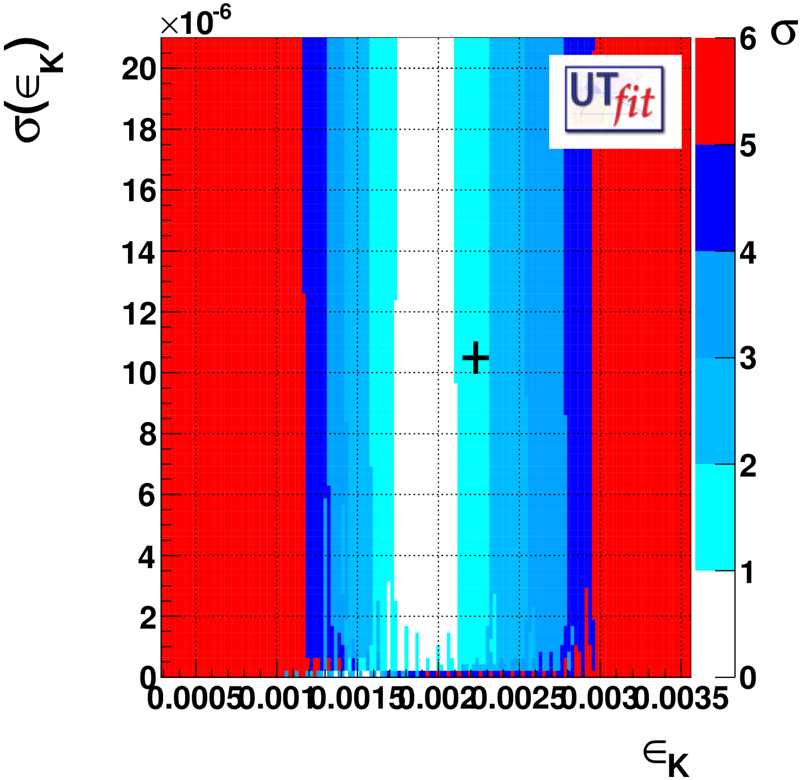
- SM prediction (UTfit, does not include NNLO η_{ct}):

  $(1.9 \pm 0.2)10^{-3}$

to be compared with

$(2.23 \pm 0.01)10^{-3}$

agreement at 1.5σ



CPV in B_q mixing in the SM & beyond

B_q mixing is governed by:

- M_{12}, dominated by the exchange of virtual heavy states (top + NP) in loops
- Γ_{12}, dominated by real intermediate states $\Rightarrow$ tree-level dominated

Assume that NP is a negligible correction to tree level processes

$M^{full}_{12} = \langle B|H^{eff}|\bar{B}\rangle = M^{SM}_{12} + M^{NP}_{12} = C_{Bq} e^{2i\phi_{Bq}} M^{SM}_{12}$

$\Gamma^{full}_{12} \sim \Gamma^{SM}_{12}$ (+ small effects due to penguins)

Notice that $\Gamma^{SM}_{12}/M^{SM}_{12}$ ~ real due to GIM suppression, since

$\Gamma^{SM}_{12} \propto (V_{tb}V_{tq}^*)^2 D^{cc}$ + GIM-suppressed

$M^{SM}_{12} \propto (V_{tb}V_{tq}^*)^2$

On the other hand,

$\mathrm{Arg}(M^{SM}_{12})_d = 2\beta \sim O(1)$

$\mathrm{Arg}(M^{SM}_{12})_s = -2\beta_s \sim O(10^{-2})$

What can we actually measure?

- $\Delta m_{Bq} = 2|M^{full}_{12}| = C_{Bq}\,\Delta m^{SM}_{Bq}$
- $\Delta\Gamma_q/\Delta m_{Bq} = \mathrm{Re}(\Gamma^{full}_{12}/M^{full}_{12}) \sim$

  $(\Delta\Gamma_q/\Delta m_{Bq})^{SM} \cos 2\phi_{Bq}/C_{Bq}$
- $A^q_{SL} = \mathrm{Im}(\Gamma^{full}_{12}/M^{full}_{12}) \sim -(\Delta\Gamma_q/\Delta m_{Bq})^{SM}\, x$

  $\sin 2\phi_{Bq}/C_{Bq} = -\Delta\Gamma_q/\Delta m_{Bq} \tan 2\phi_{Bq}$
- $S_{J/\Psi K} \sim \sin 2(\beta+\phi_{Bd}),\ S_{J/\Psi\phi} \sim \sin 2(-\beta_s+\phi_{Bs})$

- Use tree-level processes to determine the CKM matrix and thus disentangle NP from SM contributions to meson mixing:

  $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive semileptonic B decays

  γ from $B \to DK$ and α from $B \to \pi\pi, \rho\pi, \rho\rho$ decays

A FEW REMARKS

- The values of $C_{\varepsilon'}$, ϕ_{Bd} and ϕ_{Bs} extracted from the analysis potentially contain a mixture of $\Delta F=1$ & $\Delta F=2$ NP contributions. Disentangling them is a difficult task.
- For the B_s analysis, we use an improved theoretical prediction for $\Delta\Gamma$:
  $\Delta\Gamma_s/\Gamma_s=0.14\pm0.02$ — Ciuchini et al., in preparation; see also Lenz & Nierste
  and allow for NP penguin effects in Γ_{12}

Results for NP parameters:

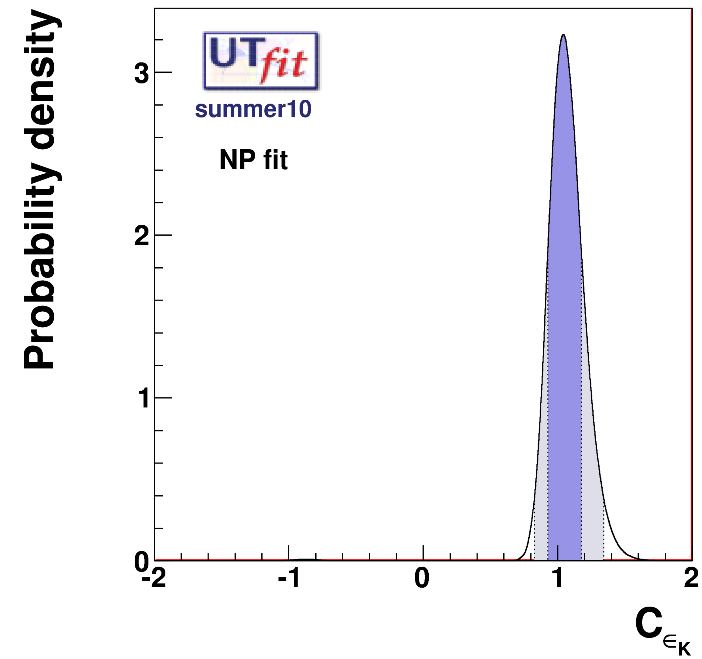
$C_{\varepsilon K}$ = 1.05 ± 0.12 [0.82,1.34]

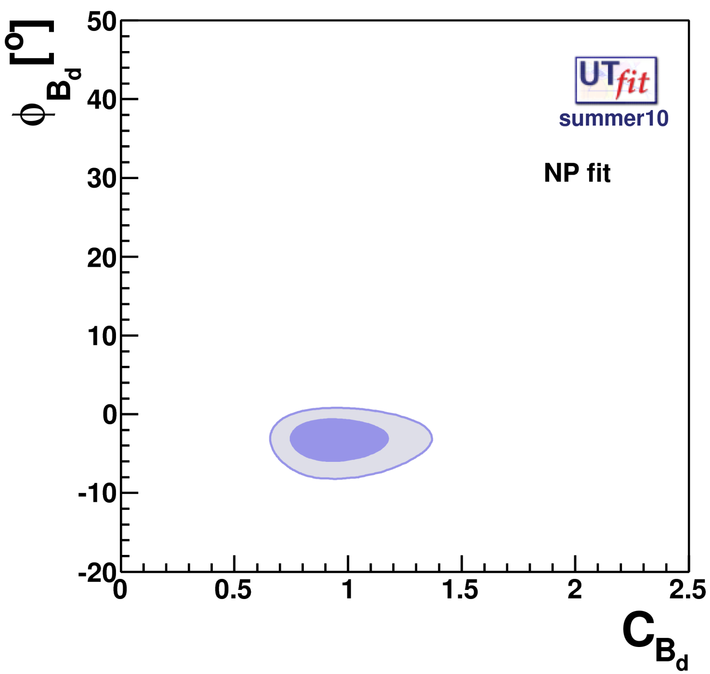
C_{Bd} = 0.95 ± 0.14 [0.70,1.27]

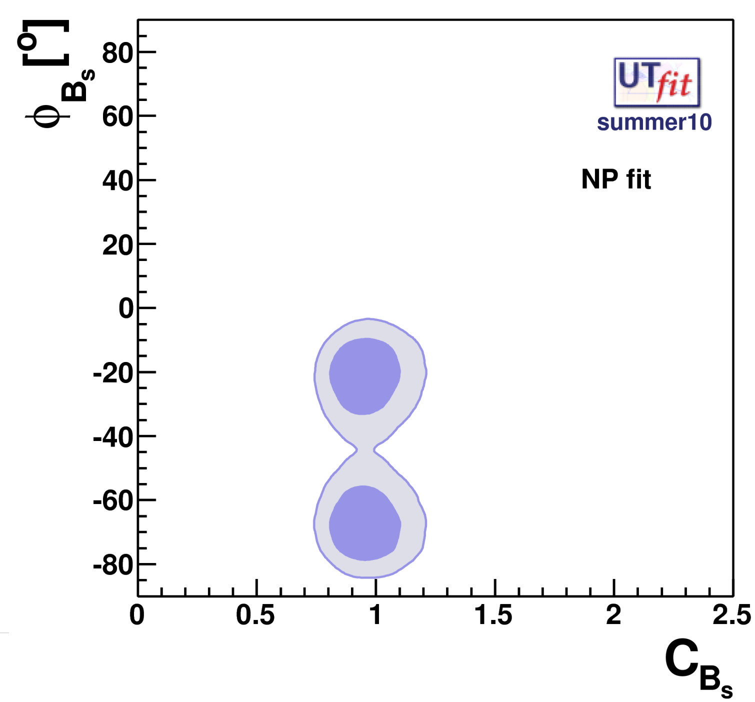
ϕ_{Bd} = (-3.1 ± 1.7)° [-7.0,0.1]°

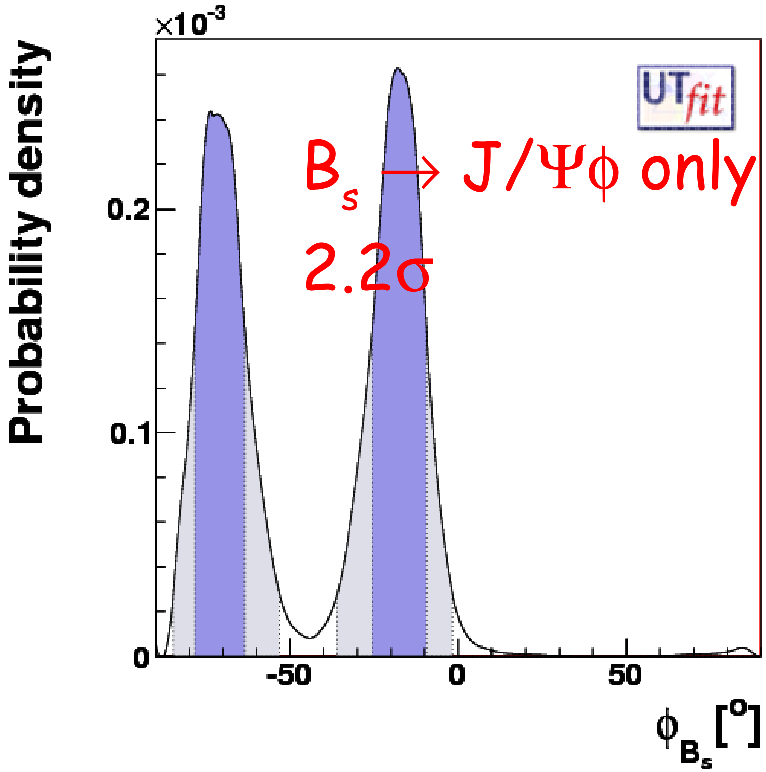
C_{Bs} = 0.95 ± 0.10 [0.77,1.16]

ϕ_{Bs} = (-20 ± 8)° U (-68 ± 8)° [-38,-6]°U[-81,-51]°



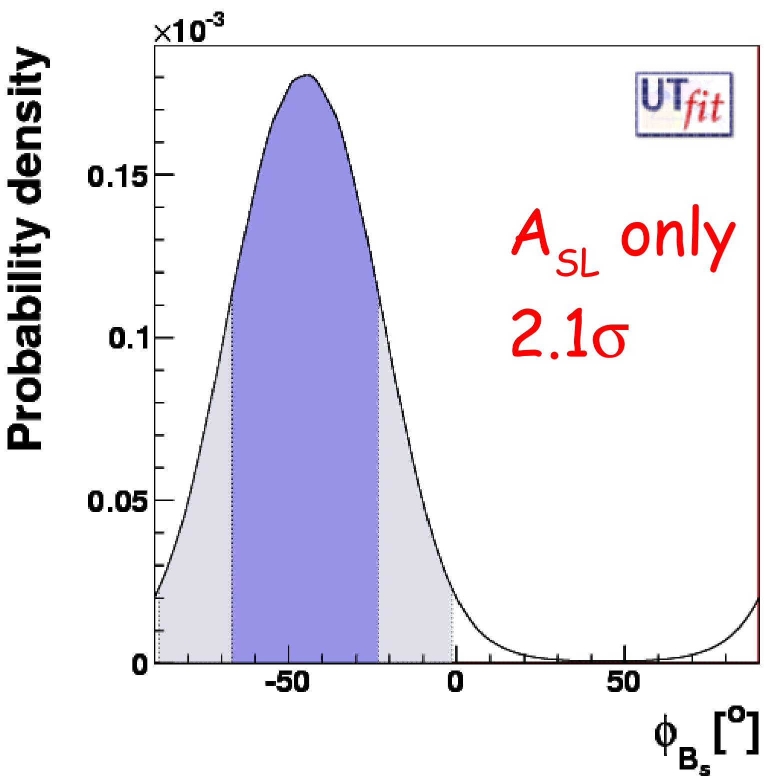


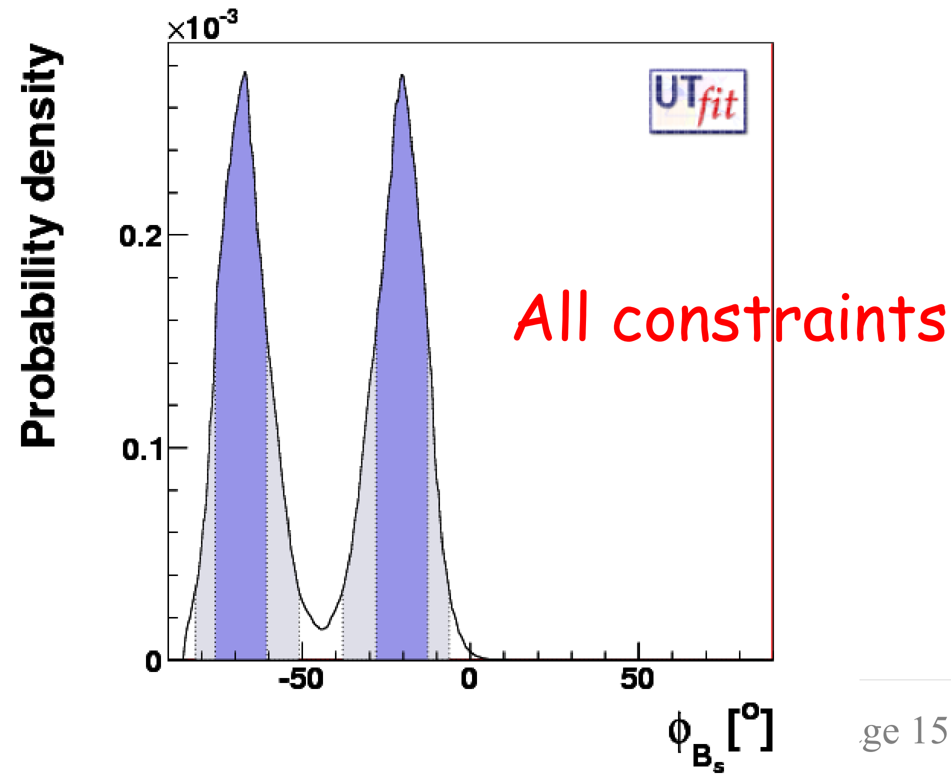




We use the combined TeVatron likelihood which does not include the new CDF result, and the recent $A_{\mu\mu}$.

Using all data we are at 3.2σ.

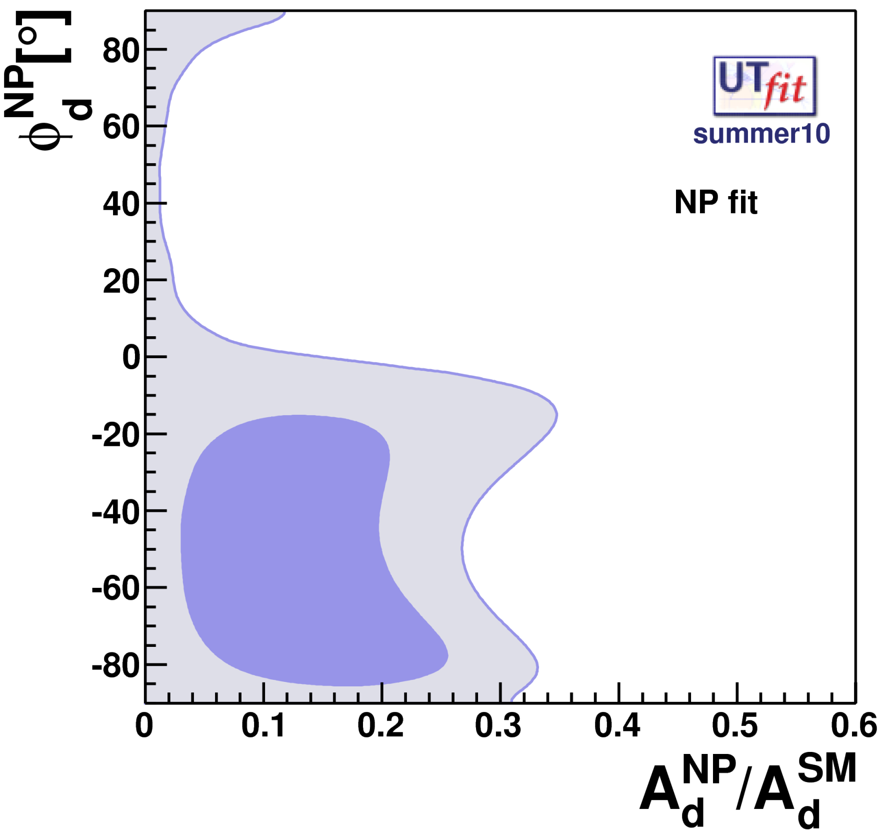


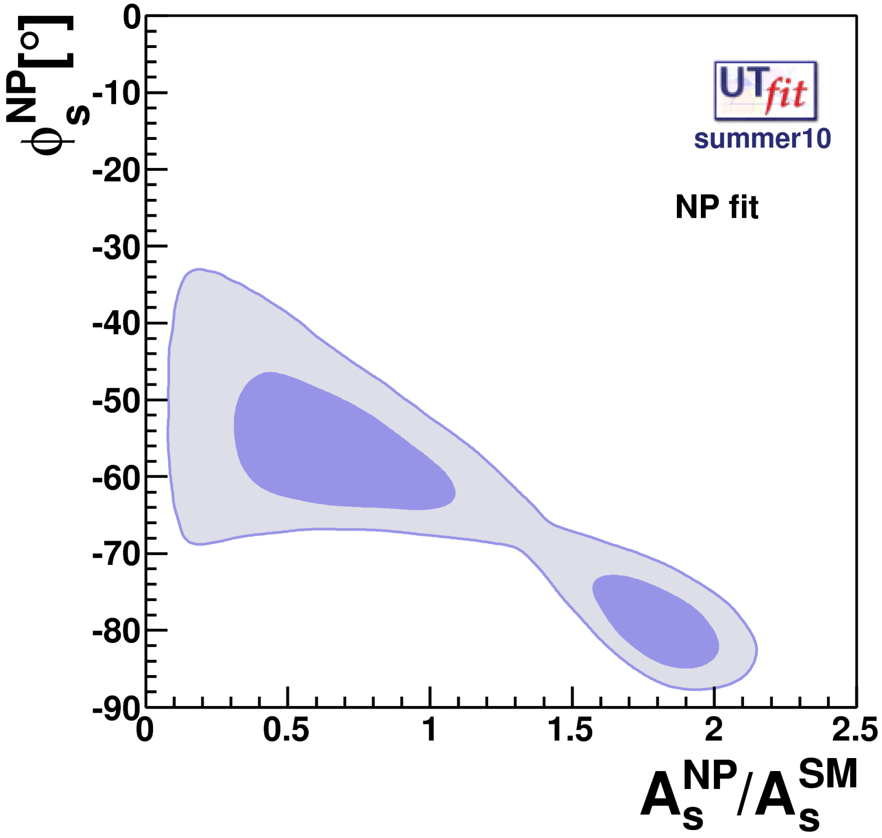


SEMILEPTONIC ASYMMETRIES

Asymmetry	Input	Prediction	Fit
$A_{SL}^{d}\,10^3$	(-0.5±5.6)	(-0.9±2.7)	(-2.8±2.4)
$A_{SL}^{s}\,10^3$	(-1.7±9.1)	(-3.7±1.5)	(-4.4±1.4)
$A_{\mu\mu}\,10^3$	(-9.6±2.9)	(-2.3±1.7)	(-3.7±1.4)

The D0 result on $A_{\mu\mu}$ cannot be reproduced given our theoretical prediction for Γ_{12} in the SM and the assumption of no tree-level NP





Ratio of NP/SM contributions is < 35% @ 95% prob. in B_d mixing, and ~70% in B_s mixing (but 2σ range is very large)

See also Lenz & Nierste, Lunghi & Soni, Buras & Guadagnoli, Faller et al, Lenz et al, ...

- Large NP contributions to b $\leftrightarrow$ s transitions are natural in nonabelian flavour models, given the large breaking of flavour SU(3) due to the top quark mass

Pomarol, Tommasini; Barbieri, Dvali, Hall; Barbieri, Hall; Barbieri, Hall, Romanino; Berezhiani, Rossi; Masiero et al; …

- GUTs can naturally connect the large mixing in ν oscillations with a large b $\leftrightarrow$ s mixing Baek et al.; Moroi; Akama et al.; Chang, Masiero, Murayama; Hisano, Shimizu; Goto et al.; …

- Might show up also in $\Delta F=1$ transitions ($b\to s\gamma$, $b\to s l^+l^-$, $B\to K\pi$, $B_s\to K^{*0}K^{*0}$, ...) and/or LFV ($\tau\to\mu\gamma$, $\mu\to e\gamma$)

EFT analysis of ΔF=2 transitions

The mixing amplitudes $A_q e^{2i\phi_q} = \langle \bar{M}_q | H_{eff}^{\Delta F=2} | M_q \rangle$

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$$Q_1 = \bar{q}_L^\alpha \gamma_\mu b_L^\alpha \, \bar{q}_L^\beta \gamma^\mu b_L^\beta \qquad \text{(SM/MFV)}$$

$$Q_2 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_R^\beta b_L^\beta \qquad Q_3 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_R^\beta b_L^\alpha$$

$$Q_4 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad Q_5 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_L^\beta b_R^\alpha$$

$$\tilde{Q}_1 = \bar{q}_R^\alpha \gamma_\mu b_R^\alpha \, \bar{q}_R^\beta \gamma^\mu b_R^\beta$$

$$\tilde{Q}_2 = \bar{q}_L^\alpha b_R^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad \tilde{Q}_3 = \bar{q}_L^\alpha b_R^\beta \, \bar{q}_L^\beta b_R^\alpha$$

7 new operators beyond MFV involving quarks with different chiralities

H_{eff} can be recast in terms of the $C_i(\Lambda)$ computed at the NP scale

- $C_i(\Lambda)$ can be extracted from the data (one by one)
- the associated NP scale Λ can be defined from

$$C_i(\Lambda) = \frac{L F_i}{\Lambda^2}$$

tree/strong interact. NP: $L \sim 1$

perturbative NP: $L \sim \alpha_s^2, \alpha_W^2$

Flavour structures:

MFV	next-to-MFV	generic
- $F_1 = F_{SM} \sim (V_{tq} V_{tb}^*)^2$ - $F_{i \neq 1} = 0$	- $\lvert F_i \rvert \sim F_{SM}$ - arbitrary phases	- $\lvert F_i \rvert \sim 1$ - arbitrary phases

present lower bound on the NP scale (TeV):

Process	C_4 (GeV^{-2})	Λ_{GEN} (TeV)	Λ_{NMFV} (TeV)
ε_K	$4.6\ 10^{-18}$	$47\ 10^4$	107
B_d	$9.3\ 10^{-14}$	$3.3\ 10^3$	7
B_s	$1.5\ 10^{-11}$	$2.6\ 10^2$	8

* $\Delta F=2$ chirality-flipping operators are RG enhanced and thus probe larger NP scales
* suppression of the $1 \leftrightarrow 2$ transitions strongly weakens the lower bounds

Bounds on Λ_{MFV} from $\Delta F=2$ processes: for low $\tan\beta$

$F_{tt} \in [-0.326, 0.487] \rightarrow \Lambda_{MFV} > 8.4\ (6.9)$ TeV

CPV in nonleptonic decays

- ε'/ε: ΔI=1/2 rule indicates large (huge) nonperturbative effects in (penguin) matrix elements

- The computation of $K \to (\pi\pi)_{I=2}$ amplitudes is progressing well, with the preliminary result for Re A_2 is good agreement with the physical value.
  - Normalized Im A_2 available soon.
  - This will become a benchmark computation which will be improved in the coming years (finer lattices?).
- The exploratory results for $K \to (\pi\pi)_{I=0}$ decays encourage us to proceed to physical kinematics.

$\Rightarrow$ an understanding of the $\Delta I = 1/2$ rule and the value of ε'/ε.

C. Sachrajda 2010

CP ASYMMETRIES IN B→Kπ

$$\mathcal{A}_{K^\pm\pi^\mp} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.094 \pm 0.018 \pm 0.008$$

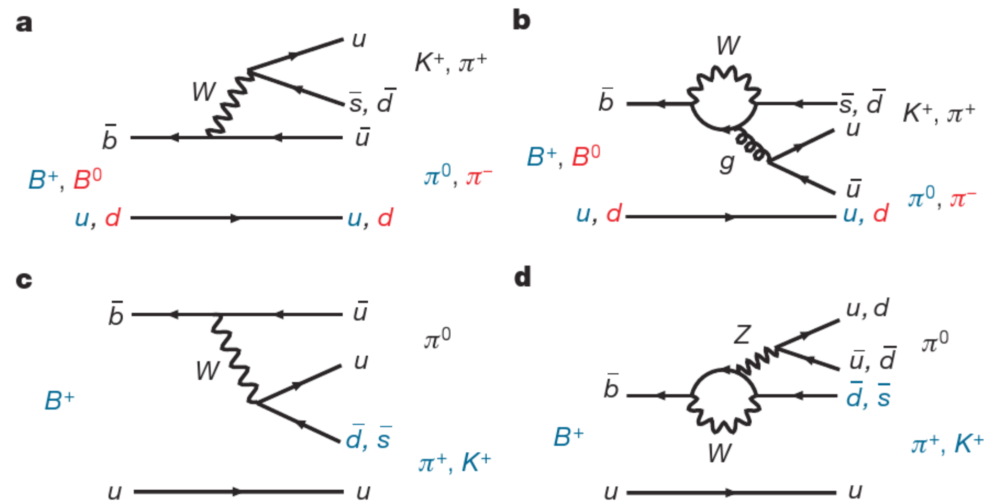
Belle collaboration
Nature 452,2008

$$\mathcal{A}_{K^\pm\pi^0} = +0.07 \pm 0.03 \pm 0.01$$

$$\Delta\mathcal{A} \equiv \mathcal{A}_{K^\pm\pi^0} - \mathcal{A}_{K^\pm\pi^\mp} = +0.164 \pm 0.037$$

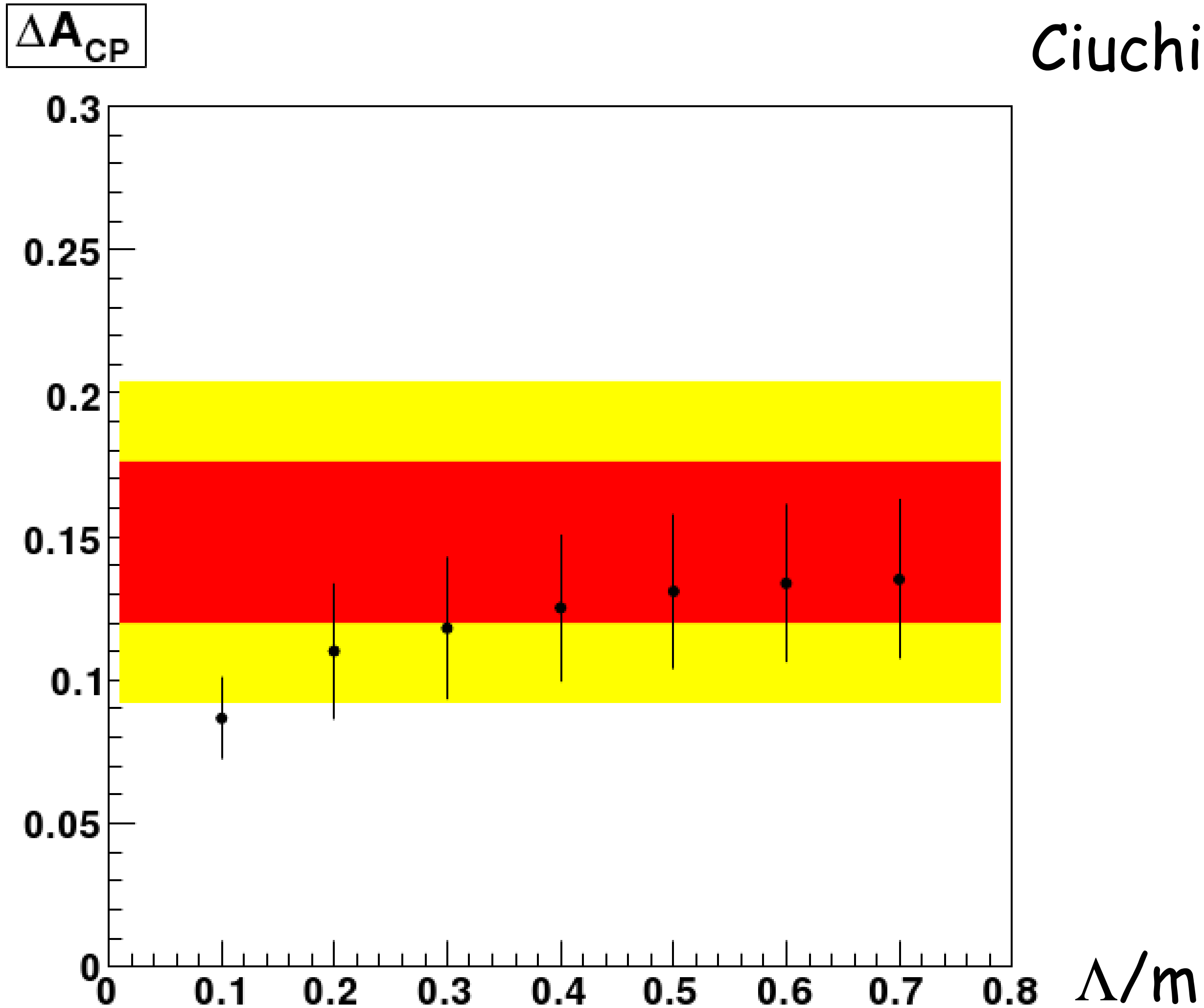
Is this new physics?

It could be but SM predictions depend on hadronic models



- Factorization in its various incarnations (QCDF, PQCD, SCET) gives results valid in the $m_b \to \infty$ limit
- Corrections to this limit are $O(\Lambda/m_b)$, but not calculable
- How much do the th predictions depend on power corrections?

Ciuchini et al. 08



A good fit can be obtained either for $\Lambda/m \sim 0.3$ or for NP in $b \to sZ$ vertex. Inconclusive at present.

See also Buraisamy & Kagan 08, Li & Mishima 09

CONCLUSIONS

- CP Violation is an extremely powerful test of the SM and probe of New Physics
- We are reaching the 5% th uncertainty on meson-antimeson mixing
- ε_K and B_d mixing give strong constraints on NP contributions, naively pushing the NP scale of several models far beyond the LHC reach

CONCLUSIONS

- CPV in B_s mixing off from SM at ~3σ
- Requires new sources of flavour & CPV, natural in many extensions of the SM
- Wait for confirmation from TeVatron/LHCb, look for other NP signals in $b \to s$ transitions
- Progress in CPV in nonleptonic decays slow and painful, but we won't give up...

BACKUP SLIDES

FIT PREDICTIONS vs INPUTS

	Prediction	Measurement	Pull (σ)
$\sin 2\beta$	0.771±0.036	0.654±0.026	2.6
α	(85±4)°	(91±6)°	<1
γ	(70±3)°	(74±11)°	<1
Δm_s	(18.3±1.3)ps^{-1}	(17.77±0.12)ps^{-1}	<1
$\lvert V_{ub}\rvert$	(35.5±1.4)10^{-4}	(37.6±2.0)10^{-4}	<1
ε_K	(1.9±0.2)10^{-3}	(2.23±0.01)10^{-3}	1.5
$BR(B\rightarrow\tau\nu)$	(81±7)10^{-6}	(172±28)10^{-6}	3.2

RESULTS OF GENERALIZED UTA

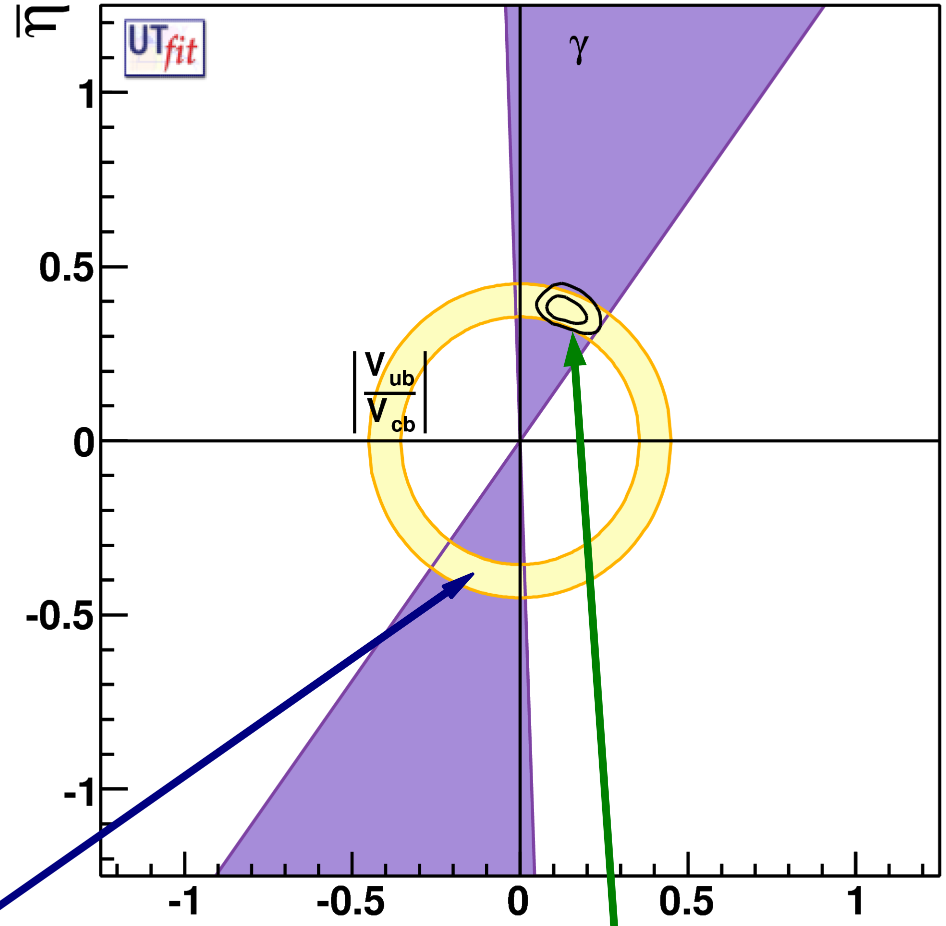
$\bar{\rho} = 0.135 \pm 0.040$

$\bar{\eta} = 0.374 \pm 0.026$

in the SM was:

$\rho = 0.132 \pm 0.020$

$\eta = 0.358 \pm 0.012$



degeneracy of γ broken by A_{SL} (assuming no huge NP effects in Γ_{12})

Accuracy improved by α (assuming no huge NP contribution to EWP)