Searching for New Physics in Heavy Flavours

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UTfit

- Introduction
- Status of flavour physics in the SM
- UT beyond the SM and constraints on NP
- CP violation in Charm Physics
- Conclusions and Outlook

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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

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!!

EXPRESS REVIEW OF THE SM

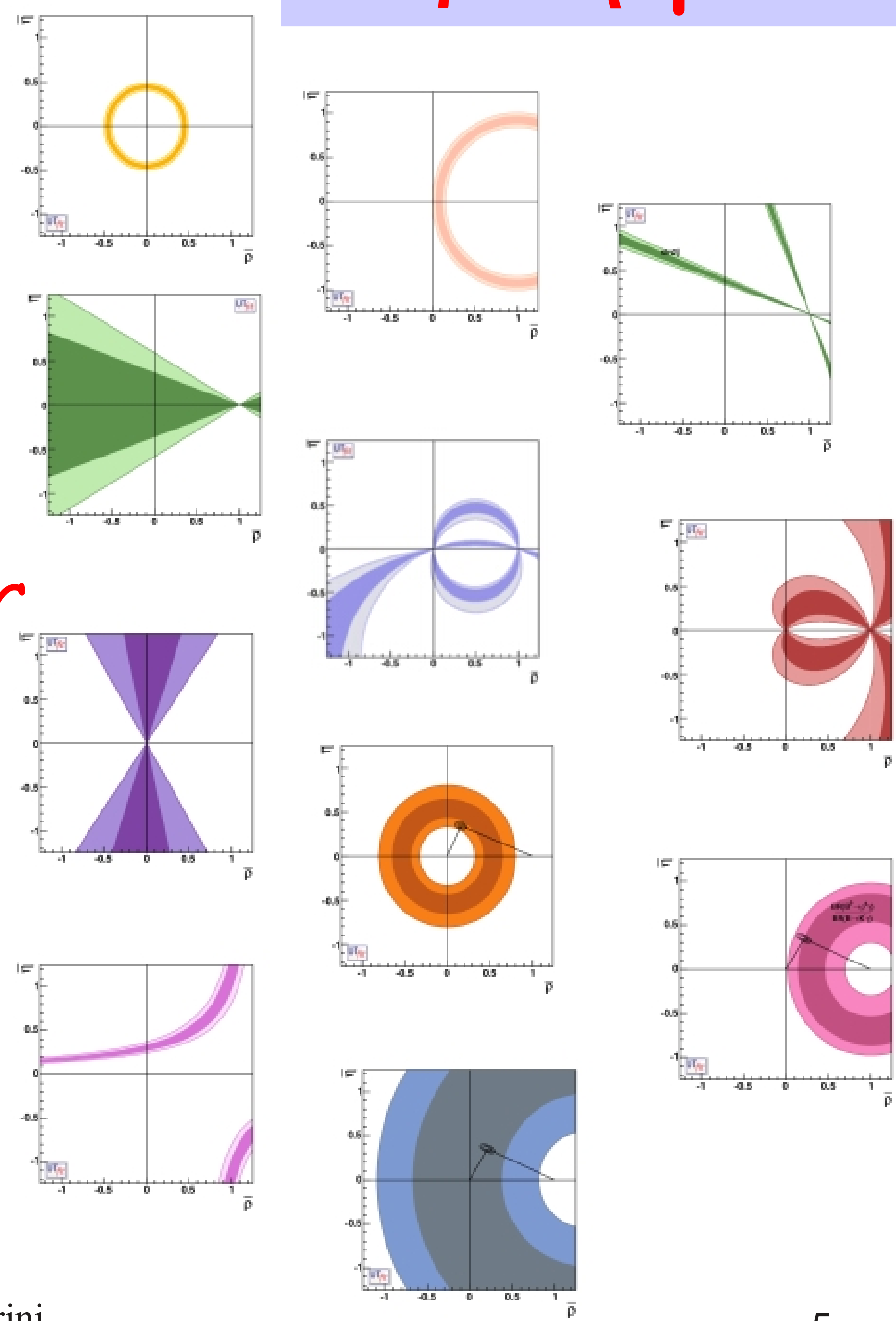
- All flavour violation from charged current coupling: CKM matrix V

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

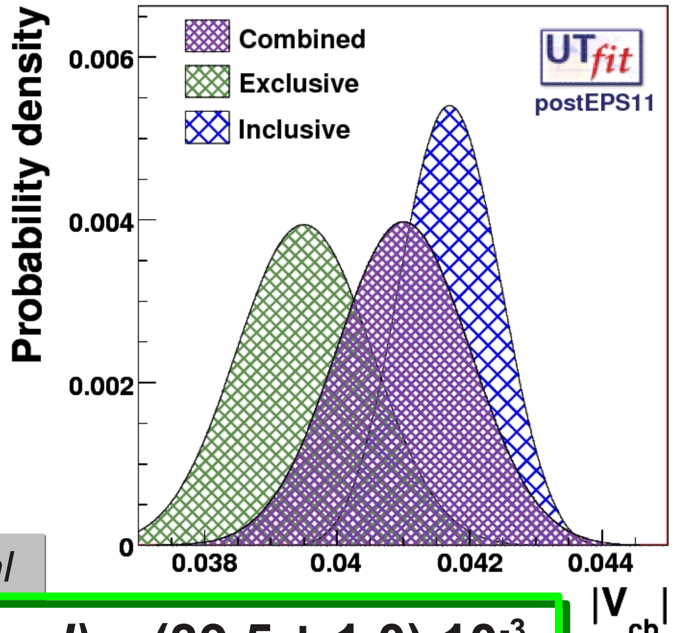
- Top quark exchange dominates FCNC loops: third row (V_{tq}) determines FCNC's $\leftrightarrow \bar\rho, \bar\eta$, apex of the Unitarity Triangle from $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 1$

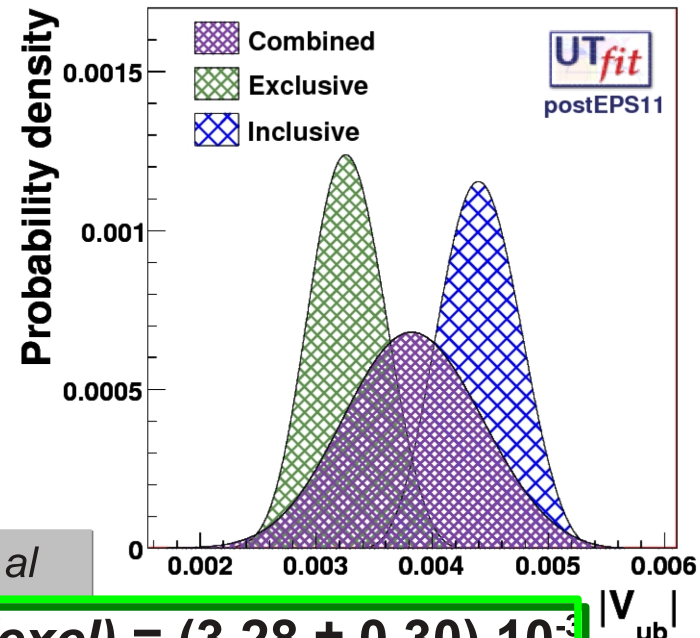
Flavour summarized on the ρ–η plane

$BR(b\to ul\nu)$, $BR(B\to\pi l\nu)$	CC
Δm_q (B_q-$\bar{B}_q$ mass diff.)	NC
$A_{CP}(b\to c\bar{c}s)$ (J/ψ K, ...)	CC
$A_{CP}(b\to s\bar{s}s$, $d\bar{d}s)$ (ϕ K, πK, ...)	NC
$A_{CP}(b\to d\bar{d}d$, $u\bar{u}d)$ ($\pi\pi$, $\rho\rho$, ...)	CC/NC
$BR(b\to c\bar{u}d$, $c\bar{u}s)$ (DK, ...)	CC
$BR(B\to\tau\nu)$	CC
$BR(B\to\rho\gamma)/BR(B\to K^*\gamma)$	NC
ε_K	NC
$K^+\to\pi^+\nu\nu$	NC



SEMILEPTONIC DECAYS





Laiho *et al*

V_{cb} *(excl)* = (39.5 ± 1.0) 10^{-3}

HFAG

V_{cb} *(incl)* = (41.7 ± 0.7) 10^{-3}

~1.8σ discrepancy

UTfit input value: average à la PDG

V_{cb} = (41.0 ± 1.0) 10^{-3}

uncertainty ~ 2.4%

Laiho *et al*

V_{ub} *(excl)* = (3.28 ± 0.30) 10^{-3}

UTfit from HFAG

V_{ub} *(incl)* = (4.40 ± 0.31) 10^{-3}

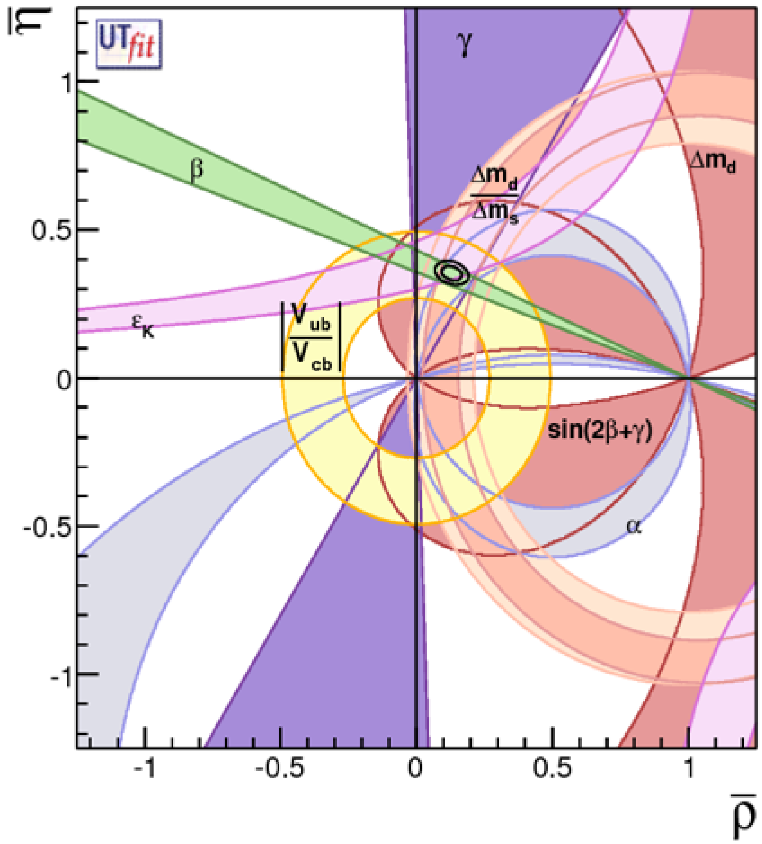
~2.6σ discrepancy

UTfit input value: average à la PDG

V_{ub} = (3.82 ± 0.56) 10^{-3}

uncertainty ~ 15%

THE OVERALL PICTURE



$\rho = 0.138 \pm 0.021$

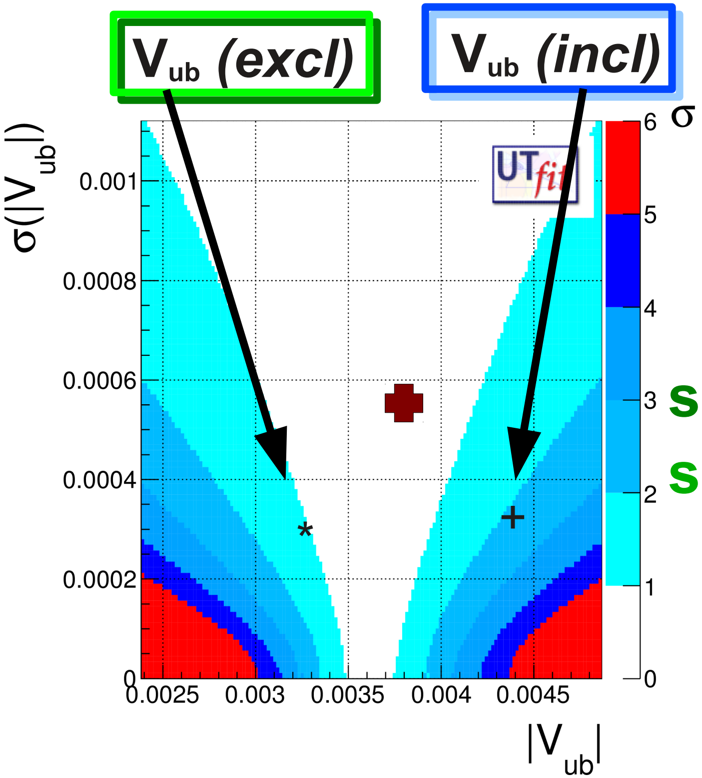
$\eta = 0.350 \pm 0.014$

$A = 0.822 \pm 0.014$

$\lambda = 0.2254 \pm 0.0006$

Parameter	Input value	Full fit	SM Prediction
f_{B_s}	0.233 ± 0.01	0.2303 ± 0.0058	$-$
f_{B_s}/f_{B_d}	1.2 ± 0.02	1.201 ± 0.018	$-$
B_{B_s}/B_{B_d}	1.05 ± 0.07	1.086 ± 0.051	$-$
B_{B_s}	0.87 ± 0.04	0.853 ± 0.036	$-$
B_k	0.75 ± 0.02	0.755 ± 0.02	0.847 ± 0.09
$\alpha[^\circ]$	91.4 ± 6.1	89.3 ± 3.0	87.9 ± 3.8
$\beta[^\circ]$	$-$	22.07 ± 0.9	26.1 ± 2.3
$\sin(2\beta)$	0.68 ± 0.023	0.697 ± 0.023	0.792 ± 0.05
$\cos(2\beta)$	0.87 ± 0.13	0.718 ± 0.022	0.616 ± 0.064
$2\beta + \gamma[^\circ]$	-90 ± 56 and 94 ± 52	112.8 ± 3.2	113.0 ± 3.2
$\gamma[^\circ]$	-103.9 ± 10.5 and 75.5 ± 10.5	68.6 ± 3.1	67.8 ± 3.2
$\lvert\epsilon_k\rvert$	$0.00222894 \pm 1.14971 \times 10^{-5}$	$0.00222754 \pm 1.0978 \times 10^{-5}$	$-$
$B(B \to \tau\nu)10^{-4}$	1.64 ± 0.34	0.857 ± 0.082	0.813 ± 0.077
$J_{cp}10^{-5}$	$-$	3.1 ± 0.12	$-$
$B(B_s \to ll), 10^{-9}$	$-$	3.45 ± 0.27	$-$

tensions



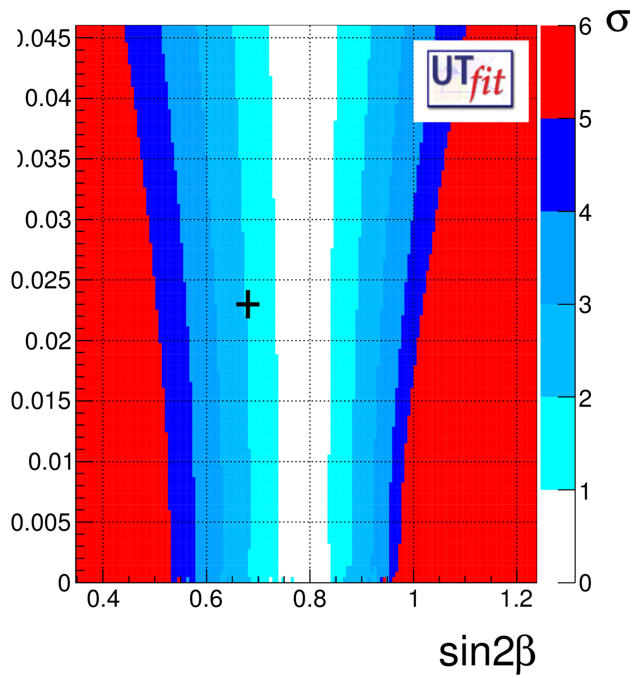
$Vub_{exp} = (3.82 \pm 0.56) \cdot 10^{-3}$

$Vub_{UTfit} = (3.62 \pm 0.14) \cdot 10^{-3}$

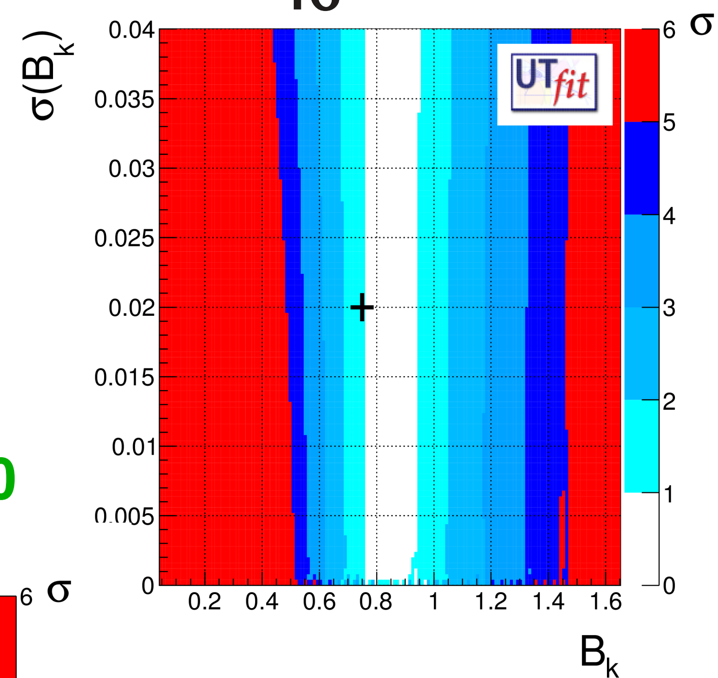
~2 σ

$\sin 2\beta_{exp} = 0.680 \pm 0.023$

$\sin 2\beta_{UTfit} = 0.792 \pm 0.050$



~1σ



$BK_{exp} = 0.750 \pm 0.020$

$BK_{UTfit} = 0.847 \pm 0.090$

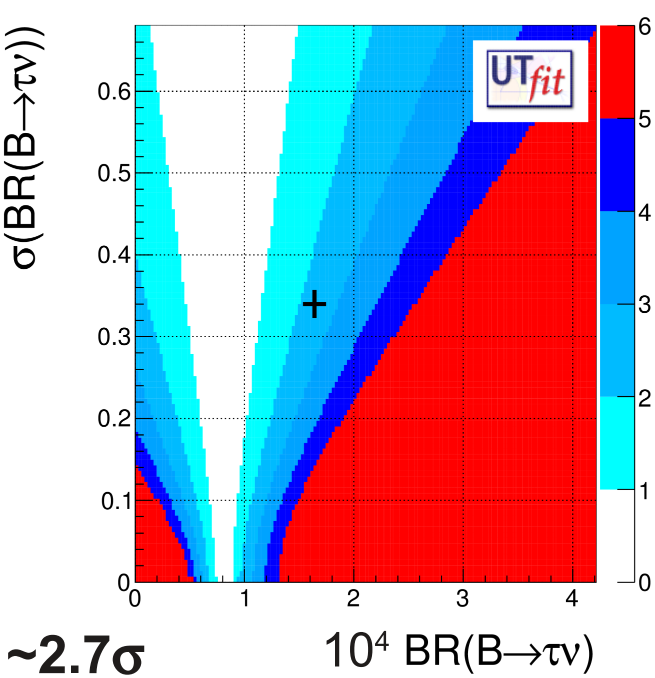
more standard model predictions:

current HFAG world average

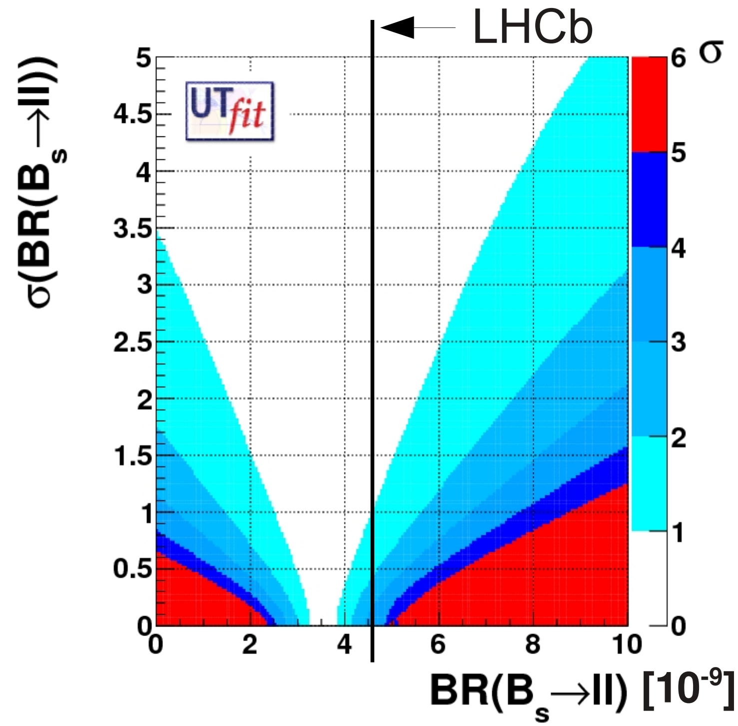
$BR(B \to \tau\nu) = (1.67 \pm 0.30)\ 10^{-4}$

best limit from LHCb

$BR(B_s \to \mu\mu) < 4.5\ 10^{-9}$



~2.7σ



indirect determinations from UT

$BR(B \to \tau\nu) = (0.82 \pm 0.08)\ 10^{-4}$

$BR(B_s \to ll) = (3.54 \pm 0.28)\ 10^{-9}$

M.Bona et al, 0908.3470 [hep-ph]

(SEMI)LEPTONIC $B \to \tau$

- (Semi)leptonic $B \to \tau$ decays seem to systematically deviate from SM predictions:
  - $BR(B \to \tau\nu)$ higher than SM prediction by 2.7σ
  - $BR(B \to D\tau\nu)/BR(B \to Dl\nu)$ higher than SM prediction by 2σ
  - $BR(B \to D^*\tau\nu)/BR(B \to D^*l\nu)$ higher than SM prediction by 2.7σ BaBar 2012
- Deviation inconsistent with 2HDMII and simple MFV models @ large $\tan\beta$ Fajfer et al 2012

UTfit beyond the Standard Model

1. fit simultaneously for the CKM and the NP parameters (generalized UT fit)
   - add most general NP to all sectors
   - use all available experimental info
   - find out how much room is left for NP in $\Delta F=2$ transitions
2. perform an $\Delta F=2$ EFT analysis to put bounds on the NP scale
   - consider different choices of the FV and CPV couplings

1. Parameterization of generic NP contributions to the mixing amplitudes

K mixing amplitude (2 real parameters):

$$\mathrm{Re}\,A_K = C_{\Delta m_K}\,\mathrm{Re}\,A_K^{SM} \qquad \mathrm{Im}\,A_K = C_\varepsilon\,\mathrm{Im}\,A_K^{SM}$$

B_d and B_s mixing amplitudes (2+2 real parameters):

$$A_q e^{2i\phi_q} = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

Observables:

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM} \qquad \varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d}) \qquad A_{CP}^{B_s \to J/\psi\phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right) \qquad \Delta\Gamma^q/\Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

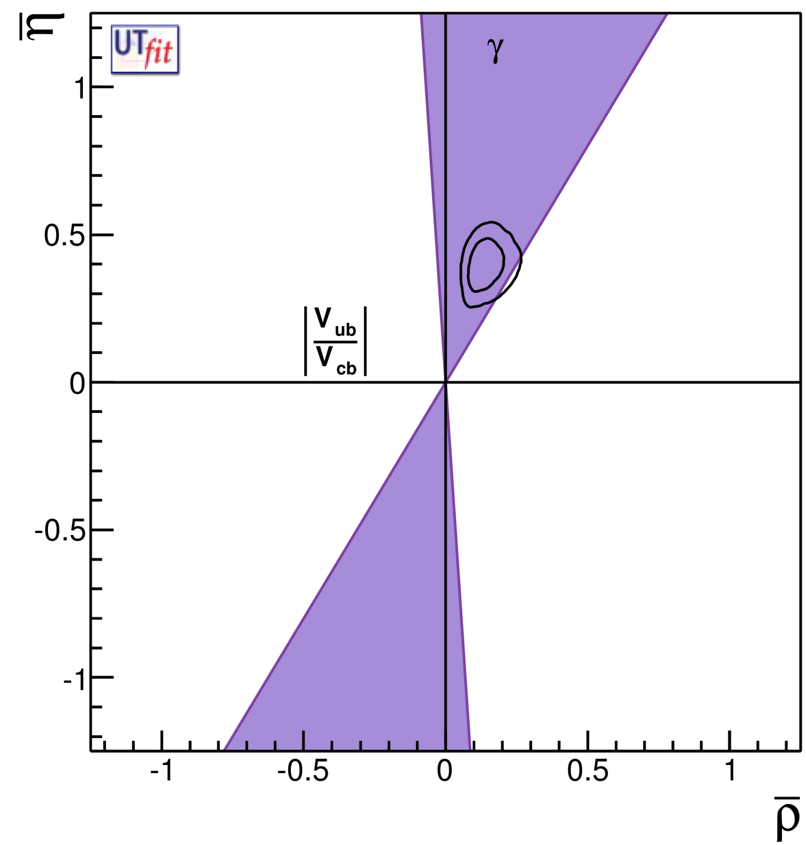
UT parameters in the presence of NP

Model-independent determination of the CKM parameters

(no NP in tree-level decays)

$\bar{\rho}$ = 0.136 ± 0.043

$\bar{\eta}$ = 0.397 ± 0.054

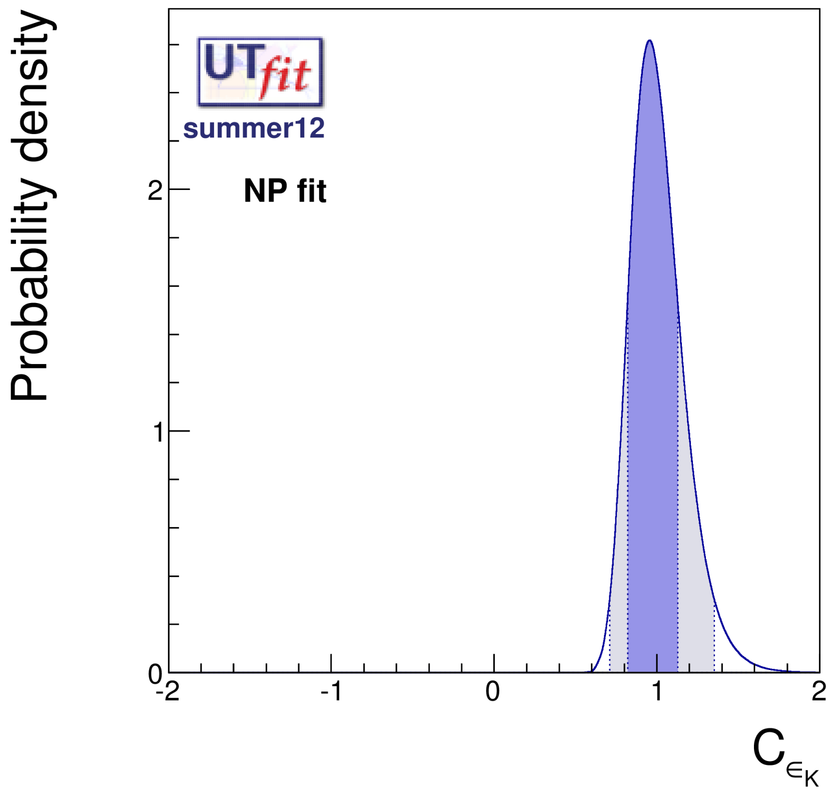


In the SM was:

$\bar{\rho}$ = 0.138 ± 0.021

$\bar{\eta}$ = 0.350 ± 0.014

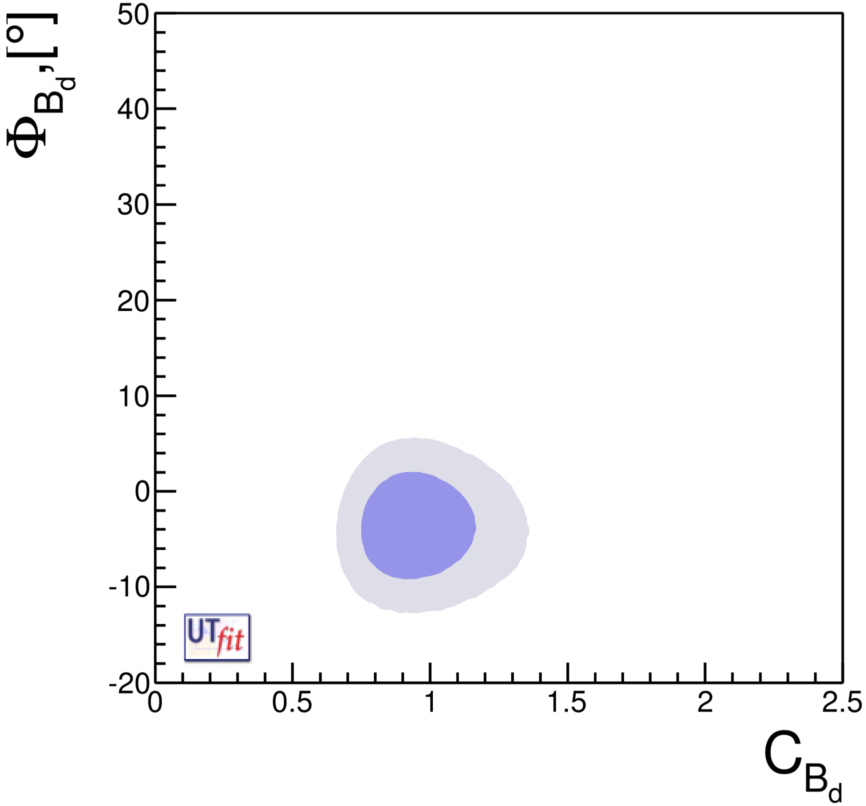
NP FIT RESULTS



- $C_{\varepsilon K}$ = 0.97 ± 0.15

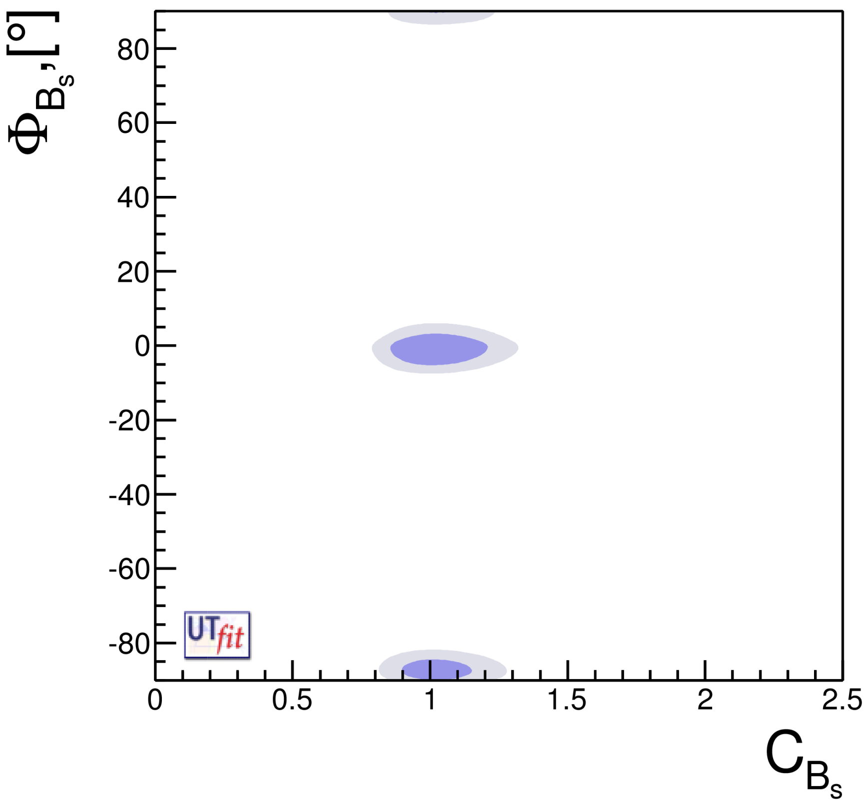
([0.70,1.35] @ 95% probability)

NP IN B_d MIXING



- $C_{Bd} = 0.94 \pm 0.14$ ([0.70,1.27] @ 95% probability)
- $\phi_{Bd} = (-3.6 \pm 3.7)^\circ$ ([-11,3.7]° @ 95% probability)

NP IN B_s MIXING



- C_{Bs} = 1.02 ± 0.10 ([0.83,1.24] @ 95% probability)
- ϕ_{Bs} = (-1.1 ± 2.8)° ([-5,4.3]° @ 95% probability)

The D0 dimuon asymmetry remains unexplained

A NOTE ON MEASURING β_s

- β_s is $O(\lambda^2)$, so must consider $O(\lambda^2)$ corrections to decay amplitudes, introducing unavoidable correlation with other CKM elements
- Subleading corrections can be controlled using suitable U-spin related control channels
- $B_s \to J/\Psi\phi$ is problematic since it has no simple control channels; $B_s \to KK$ look better

$D-\bar{D}$ MIXING

- Established experimentally only in 2007
- Great experimental progress recently
- SM long distance contributions difficult to estimate, but solid prediction: no CPV in mixing
- Direct CPV possible in SCS decays (and recently observed by LHCb and CDF)

BASIC FORMULAE

- All mixing-related observables can be expressed in terms of $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$ and $|q/p|$, or better in terms of M_{12}, Γ_{12} and $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$:

$$|M_{12}| = \frac{1}{\tau_D}\sqrt{\frac{x^2+\delta^2 y^2}{4(1-\delta^2)}}\,, \quad |\Gamma_{12}| = \frac{1}{\tau_D}\sqrt{\frac{y^2+\delta^2 x^2}{1-\delta^2}}\,, \quad \sin\Phi_{12} = \frac{|\Gamma_{12}|^2+4|M_{12}|^2-(x^2+y^2)|q/p|^2/\tau_D^2}{4|M_{12}\Gamma_{12}|}$$

$$\delta = \frac{1-|q/p|^2}{1+|q/p|^2}\,, \quad \phi = \arg(q/p) = \arg(y+i\delta x)\,, \quad A_M = \frac{|q/p|^4-1}{|q/p|^4+1}\,, \quad R_M = \frac{x^2+y^2}{2}\,, \qquad (1)$$

$$\begin{pmatrix} x'_f \\ y'_f \end{pmatrix} = \begin{pmatrix} \cos\delta_f & \sin\delta_f \\ -\sin\delta_f & \cos\delta_f \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, \quad (x'_\pm)_f = \left|\frac{q}{p}\right|^{\pm1}(x'_f\cos\phi \pm y'_f\sin\phi)\,, \quad (y'_\pm)_f = \left|\frac{q}{p}\right|^{\pm1}(y'_f\cos\phi \mp x'_f\sin\phi)\,,$$

$$y_{\rm CP} = \left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)\frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)\frac{x}{2}\sin\phi\,, \quad A_\Gamma = \left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)\frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)\frac{x}{2}\sin\phi\,,$$

$$R_D = \frac{\Gamma(D^0\to K^+\pi^-)+\Gamma(\bar{D}^0\to K^-\pi^+)}{\Gamma(D^0\to K^-\pi^+)+\Gamma(\bar{D}^0\to K^+\pi^-)}\,, \quad A_D = \frac{\Gamma(D^0\to K^+\pi^-)-\Gamma(\bar{D}^0\to K^-\pi^+)}{\Gamma(D^0\to K^+\pi^-)+\Gamma(\bar{D}^0\to K^-\pi^+)}\,,$$

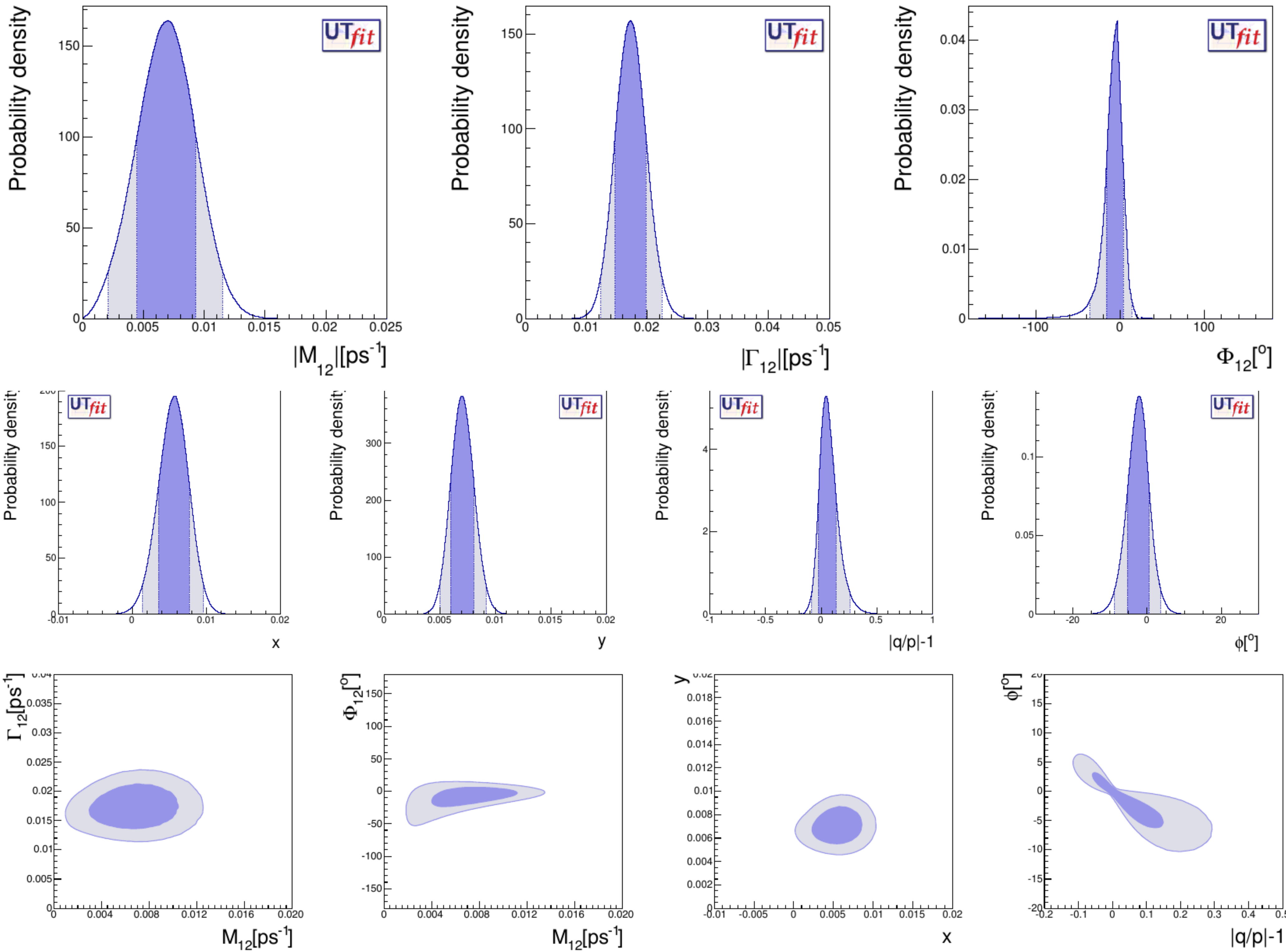
Experimental input from B-factories, CLEO-C, TeVatron and LHCb

Observable	Value	Correlation Coeff.					Reference
y_{CP}	$(0.866 \pm 0.155)\%$						[2, 17–25]
A_Γ	$(0.022 \pm 0.161)\%$						[2, 20, 23–26]
x	$(0.811 \pm 0.334)\%$	1	-0.007	-0.255α	0.216		[3]
y	$(0.309 \pm 0.281)\%$	-0.007	1	-0.019α	-0.280		[3]
$\|q/p\|$	$(0.95 \pm 0.22 \pm 0.10)\%$	-0.255α	-0.019α	1	-0.128 α		[3]
ϕ	$(-0.035 \pm 0.19 \pm 0.09)$	0.216	-0.280	-0.128 α	1		[3]
x	$(0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$	1	0.0615				[27]
y	$(0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$	0.0615	1				[27]
R_M	$(0.0130 \pm 0.0269)\%$						[28–32]
$(x'_+)_{K\pi\pi^0}$	$(2.48 \pm 0.59 \pm 0.39)\%$	1	-0.69				[33]
$(y'_+)_{K\pi\pi^0}$	$(-0.07 \pm 0.65 \pm 0.50)\%$	-0.69	1				[33]
$(x'_-)_{K\pi\pi^0}$	$(3.50 \pm 0.78 \pm 0.65)\%$	1	-0.66				[33]
$(y'_-)_{K\pi\pi^0}$	$(-0.82 \pm 0.68 \pm 0.41)\%$	-0.66	1				[33]
x^2	$(0.1549 \pm 0.2223)\%$	1	-0.6217	-0.00224	0.3698	0.01567	[34]
y	$(2.997 \pm 2.293)\%$	-0.6217	1	0.00414	-0.5756	-0.0243	[34]
R_D	$(0.4118 \pm 0.0948)\%$	-0.00224	0.00414	1	0.0035	0.00978	[34]
$2\sqrt{R_D}\cos\delta_{K\pi}$	$(12.64 \pm 2.86)\%$	0.3698	-0.5756	0.0035	1	0.0471	[34]
$2\sqrt{R_D}\sin\delta_{K\pi}$	$(-0.5242 \pm 6.426)\%$	0.01567	-0.0243	0.00978	0.0471	1	[34]
R_D	$(0.3030 \pm 0.0189)\%$	1	0.77	-0.87			[1]
$(x'_+)^2_{K\pi}$	$(-0.024 \pm 0.052)\%$	0.77	1	-0.94			[1]
$(y'_+)_{K\pi}$	$(0.98 \pm 0.78)\%$	-0.87	-0.94	1			[1]
A_D	$(-2.1 \pm 5.4)\%$	1	0.77	-0.87			[1]
$(x'_-)^2_{K\pi}$	$(-0.020 \pm 0.050)\%$	0.77	1	-0.94			[1]
$(y'_-)_{K\pi}$	$(0.96 \pm 0.75)\%$	-0.87	-0.94	1			[1]
R_D	$(0.364 \pm 0.018)\%$	1	0.655	-0.834			[35]
$(x'_+)^2_{K\pi}$	$(0.032 \pm 0.037)\%$	0.655	1	-0.909			[35]
$(y'_+)_{K\pi}$	$(-0.12 \pm 0.58)\%$	-0.834	-0.909	1			[35]
A_D	$(2.3 \pm 4.7)\%$	1	0.655	-0.834			[35]
$(x'_-)^2_{K\pi}$	$(0.006 \pm 0.034)\%$	0.655	1	-0.909			[35]
$(y'_-)_{K\pi}$	$(0.20 \pm 0.54)\%$	-0.834	-0.909	1			[35]
CP asymmetry	Value	$\Delta\langle t\rangle/\tau_{D^0}$					Reference
$A_{\rm CP}(D^0 \to K^+K^-)$	$(-0.24 \pm 0.24)\%$						[36, 37]
$A_{\rm CP}(D^0 \to \pi^+\pi^-)$	$(0.11 \pm 0.39)\%$						[36, 37]
$\Delta A_{\rm CP}$	$(-0.82 \pm 0.21 \pm 0.11)\%$	$(9.83 \pm 0.22 \pm 0.19)\%$					[9]
$\Delta A_{\rm CP}$	$(-0.62 \pm 0.21 \pm 0.10)\%$	$(26 \pm 1)\%$					[10]

FIT RESULTS

parameter	result @ 68% prob.	95% prob. range
$\|M_{12}\|$ [1/ps]	$(6.9 \pm 2.4) \cdot 10^{-3}$	$[2.1, 11.5] \cdot 10^{-3}$
$\|\Gamma_{12}\|$ [1/ps]	$(17.2 \pm 2.5) \cdot 10^{-3}$	$[12.3, 22.4] \cdot 10^{-3}$
Φ_{12} [°]	(-6 ± 9)	$[-37, 13]$
x	$(5.6 \pm 2.0) \cdot 10^{-3}$	$[1.4, 9.6] \cdot 10^{-3}$
y	$(7.0 \pm 1.0) \cdot 10^{-3}$	$[5.0, 9.1] \cdot 10^{-3}$
$\|q/p\| - 1$	$(5.3 \pm 7.7) \cdot 10^{-2}$	$[-8.5, 25.6] \cdot 10^{-2}$
ϕ [°]	(-2.4 ± 2.9)	$[-8.8, 3.7]$
A_Γ	$(0.7 \pm 0.8) \cdot 10^{-3}$	$[-0.9, 2.3] \cdot 10^{-3}$
A_M	$(11 \pm 14) \cdot 10^{-2}$	$[-15, 44] \cdot 10^{-2}$
R_M	$(4.0 \pm 1.4) \cdot 10^{-5}$	$[1.7, 7.2] \cdot 10^{-5}$
R_D	$(3.27 \pm 0.08) \cdot 10^{-3}$	$[3.10, 3.44] \cdot 10^{-3}$
$\delta_{K\pi}$ [°]	(18 ± 12)	$[-14, 40]$
$\delta_{K\pi\pi^0}$ [°]	(31 ± 20)	$[-11, 73]$
$a_{\rm CP}^{\rm dir}(D^0 \to K^+K^-)$	$(-2.6 \pm 2.2) \cdot 10^{-3}$	$[-7.1, 1.9] \cdot 10^{-3}$
$a_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$	$(4.1 \pm 2.4) \cdot 10^{-3}$	$[-0.8, 9.0] \cdot 10^{-3}$
$\Delta a_{\rm CP}^{\rm dir}$	$(6.6 \pm 1.6) \cdot 10^{-3}$	$[-9.8, 3.5] \cdot 10^{-3}$

TABLE II. Results of the fit to D mixing data. $\Delta a_{\rm CP}^{\rm dir} = a_{\rm CP}^{\rm dir}(D^0 \to K^+K^-) - a_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$.


Probability density
UTfit
|M12|[ps-1]
|Γ12|[ps-1]
Φ12[o]
x
y
|q/p|-1
φ[o]
Γ12[ps-1]
M12[ps-1]
Φ12[o]
M12[ps-1]
y
x
φ[o]
|q/p|-1

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

present lower bound on the NP scale for $L=1$ and $F_i = 1$:

from ε_K: 4.9 10^5 TeV

from D mixing: 1.3 10^4 TeV

from B_d mixing: 3 10^3 TeV

from B_s mixing: 8 10^2 TeV

* $\Delta F=2$ chirality-flipping operators are RG enhanced and thus probe larger NP scales
* when these operators are allowed, the NP scale is easily pushed beyond the LHC reach
* suppression of the 1 <-> 2 transitions strongly weakens the lower bounds

DIRECT CPV IN CHARM DECAYS

- Some basic facts known for a long time:

1) To obtain a good description of SCS D BR's need:
   - final state interactions and corrections to factorization
   - sizable SU(3) breaking

2) The SM expectation for direct CPV is $\lesssim 10^{-3}$

See for example Buccella et al. '95

EXPERIMENTAL STATUS

- Very recently, LHCb and CDF provided evidence of $\Delta A_{CP}=A_{CP}(K^+K^-)-A_{CP}(\pi^+\pi^-)$
- Combining LHCb, CDF and B-factories:

$a_{\rm CP}^{\rm dir}(D^0 \to K^+K^-)$	$(-2.6 \pm 2.2)\cdot 10^{-3}$	$[-7.1, 1.9]\cdot 10^{-3}$
$a_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$	$(4.1 \pm 2.4)\cdot 10^{-3}$	$[-0.8, 9.0]\cdot 10^{-3}$
$\Delta a_{\rm CP}^{\rm dir}$	$(6.6 \pm 1.6)\cdot 10^{-3}$	$[-9.8, 3.5]\cdot 10^{-3}$

well above the 10^{-3} barrier…

THEORY QUESTIONS

- Can we envisage a mechanism to enhance the SM prediction for CPV by one order of magnitude to reproduce the exp result?

Brod, Kagan & Zupan '11; Pirtskhalava & Uttayarat '11; Bhattacharya, Gronau & Rosner '12; Cheng & Chiang '12; Brod, Grossman, Kagan & Zupan '12

- Can anything analogous to the $\Delta I=1/2$ rule take place in SCS charm decays?

Golden & Grinstein, '89

ISOSPIN & UNITARITY

- Let us start from the basic knowledge:
  - SU(3) breaking is large ⇒ use only isospin
  - corrections to factorization are large ⇒ use a general parameterization
  - final state interactions are important ⇒ implement unitarity & external info on rescattering

Franco, Mishima & LS '12

ISOSPIN AMPLITUDES

r_{CKM}=6.4 10^{-4}

A CP-even

B CP-odd

$$A(D^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2}\mathcal{A}_2^\pi \,,$$

$$A(D^0 \to \pi^+\pi^-) = \frac{\mathcal{A}_2^\pi - \sqrt{2}(\mathcal{A}_0^\pi + i r_{\rm CKM}\mathcal{B}_0^\pi)}{\sqrt{6}} \,,$$

$$A(D^0 \to \pi^0\pi^0) = \frac{\sqrt{2}\mathcal{A}_2^\pi + \mathcal{A}_0^\pi + i r_{\rm CKM}\mathcal{B}_0^\pi}{\sqrt{3}} \,,$$

$$A(D^+ \to K^+\bar{K}^0) = \frac{\mathcal{A}_{13}^K}{2} + \mathcal{A}_{11}^K + i r_{\rm CKM}\mathcal{B}_{11}^K \,,$$

$$A(D^0 \to K^+K^-) = \frac{-\mathcal{A}_{13}^K + \mathcal{A}_{11}^K - \mathcal{A}_0^K + i r_{\rm CKM}\mathcal{B}_{11}^K - i r_{\rm CKM}\mathcal{B}_0^K}{2} \,,$$

$$A(D^0 \to K^0\bar{K}^0) = \frac{-\mathcal{A}_{13}^K + \mathcal{A}_{11}^K + \mathcal{A}_0^K + i r_{\rm CKM}\mathcal{B}_{11}^K + i r_{\rm CKM}\mathcal{B}_0^K}{2} \,.$$

NUMERICAL RESULTS FROM BR's

$$|\mathcal{A}_2^\pi| = (3.08 \pm 0.08) \times 10^{-7}\ \mathrm{GeV}\,,$$

$$|\mathcal{A}_0^\pi| = (7.6 \pm 0.1) \times 10^{-7}\ \mathrm{GeV}\,,$$

$$\arg(\mathcal{A}_2^\pi/\mathcal{A}_0^\pi) = (\pm 93 \pm 3)^\circ\,.$$

No ΔI=1/2 rule for D decays, large strong phases

$$|\mathcal{A}_{13}^K - \mathcal{A}_{11}^K - \mathcal{A}_0^K| = (5.0 \pm 0.4) \times 10^{-7}\ \mathrm{GeV}$$

Should vanish in the SU(3) limit, but is O(1)!!

UNITARITY CONSTRAINTS

$$S = \left(\begin{array}{c|ccc} D \to D & D \to \pi\pi & D \to KK & \cdots \\ \hline \pi\pi \to D & \pi\pi \to \pi\pi & \pi\pi \to KK & \cdots \\ KK \to D & KK \to \pi\pi & KK \to KK & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{array} \right) \equiv \left(\begin{array}{cc} 1 & -i(T)^T \\ -i\,\mathrm{CP}(T) & S_S \end{array} \right)$$

implies

$$T^R = S_S (T^R)^*, \qquad T^I = S_S (T^I)^*$$

Elastic case: $S = e^{2i\delta} \Rightarrow$ Watson theorem:

$T^R = |T^R| e^{i\delta}$, $T^I = |T^I| e^{i\delta}$

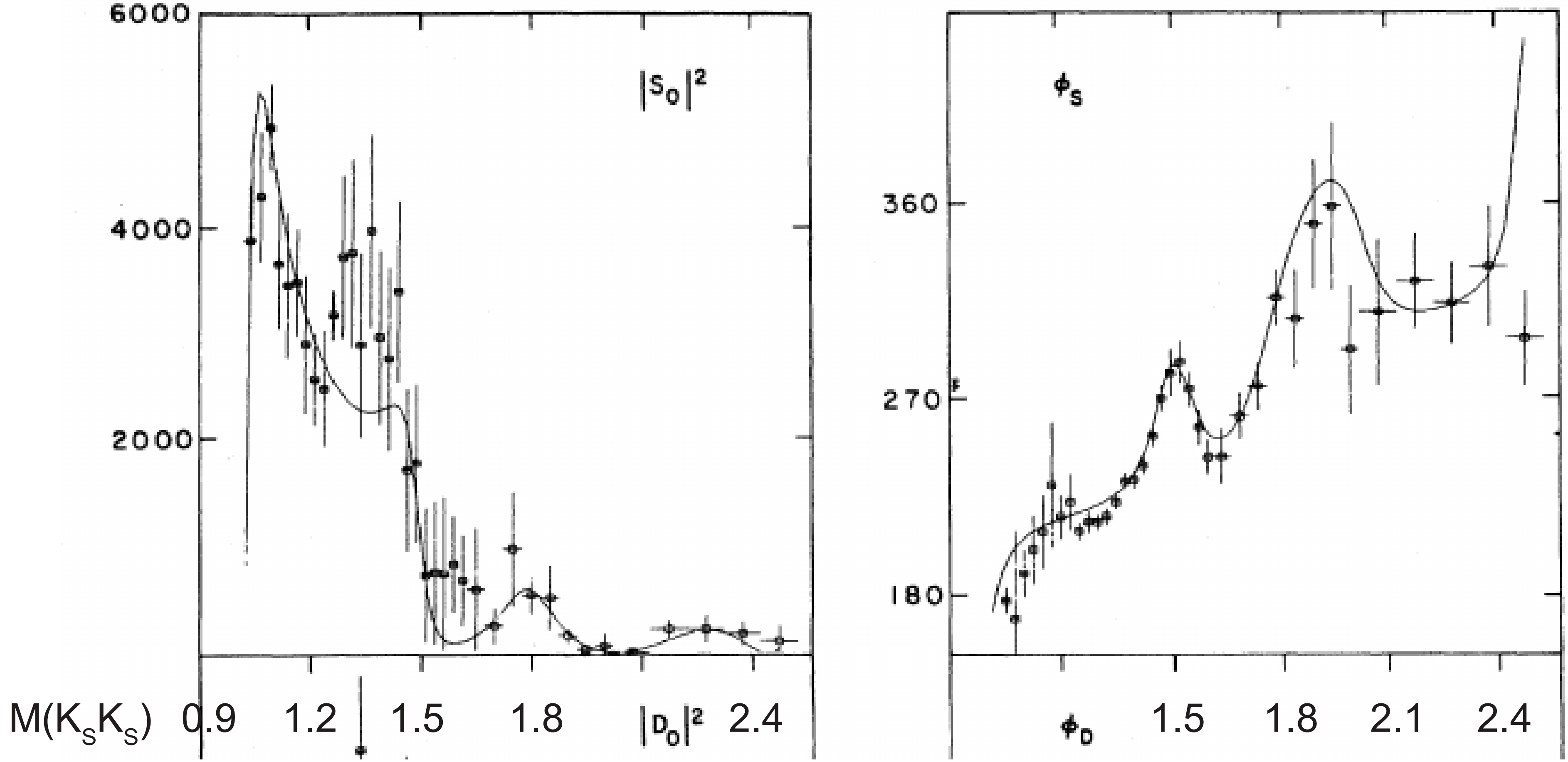
2-CHANNEL UNITARITY

$$\begin{pmatrix} \mathcal{A}_0^\pi \\ \mathcal{A}_0^K \end{pmatrix} = \begin{pmatrix} \eta\, e^{2i\delta_1} & \pm i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} \\ \pm i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} & \eta\, e^{2i\delta_2} \end{pmatrix} \begin{pmatrix} (\mathcal{A}_0^\pi)^* \\ (\mathcal{A}_0^K)^* \end{pmatrix}$$

Obtain constraints on magnitudes and phases of amplitudes

For η close to 1, magnitudes almost unconstrained but phases close to δ_1 and δ_2

Is the 2-channel S-matrix unitary at the D mass?



Etkin et al. '82

S_{12} has small amplitude and small phase.

Is this compatible with measured S_{11}?

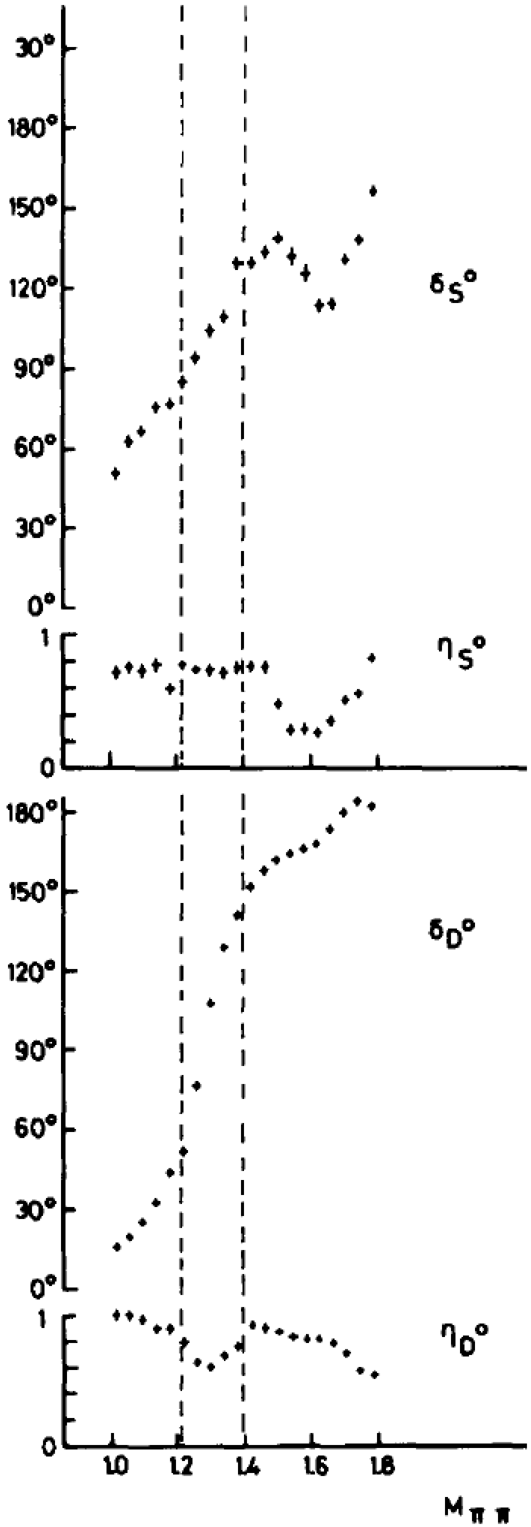


Fig. 4. Soluti

Unfortunately, πN scattering alone is ambiguous; different fits corresponding to discrete ambiguities yield widely different results close to the D mass. 2- and 3-channel unitarity possible.

Hyams et al. '73

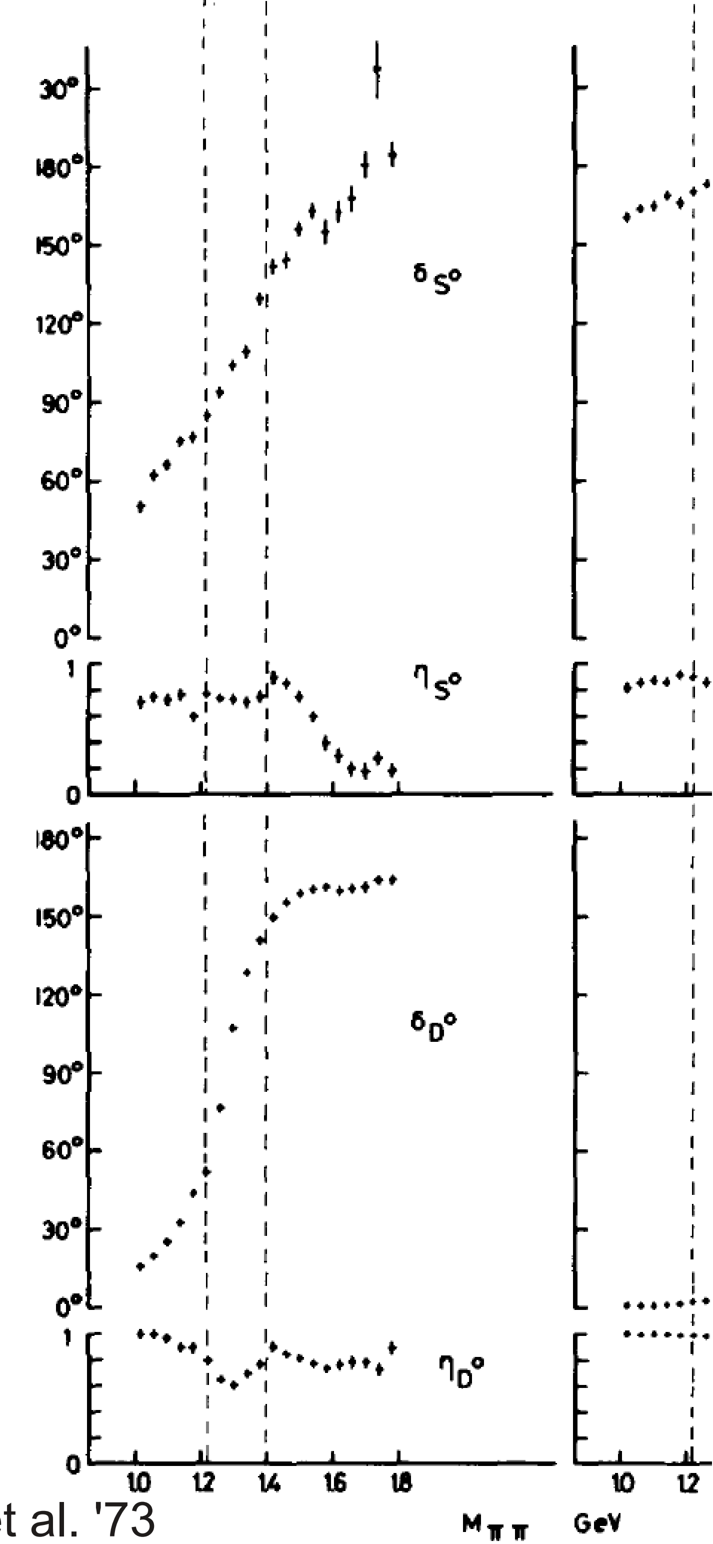


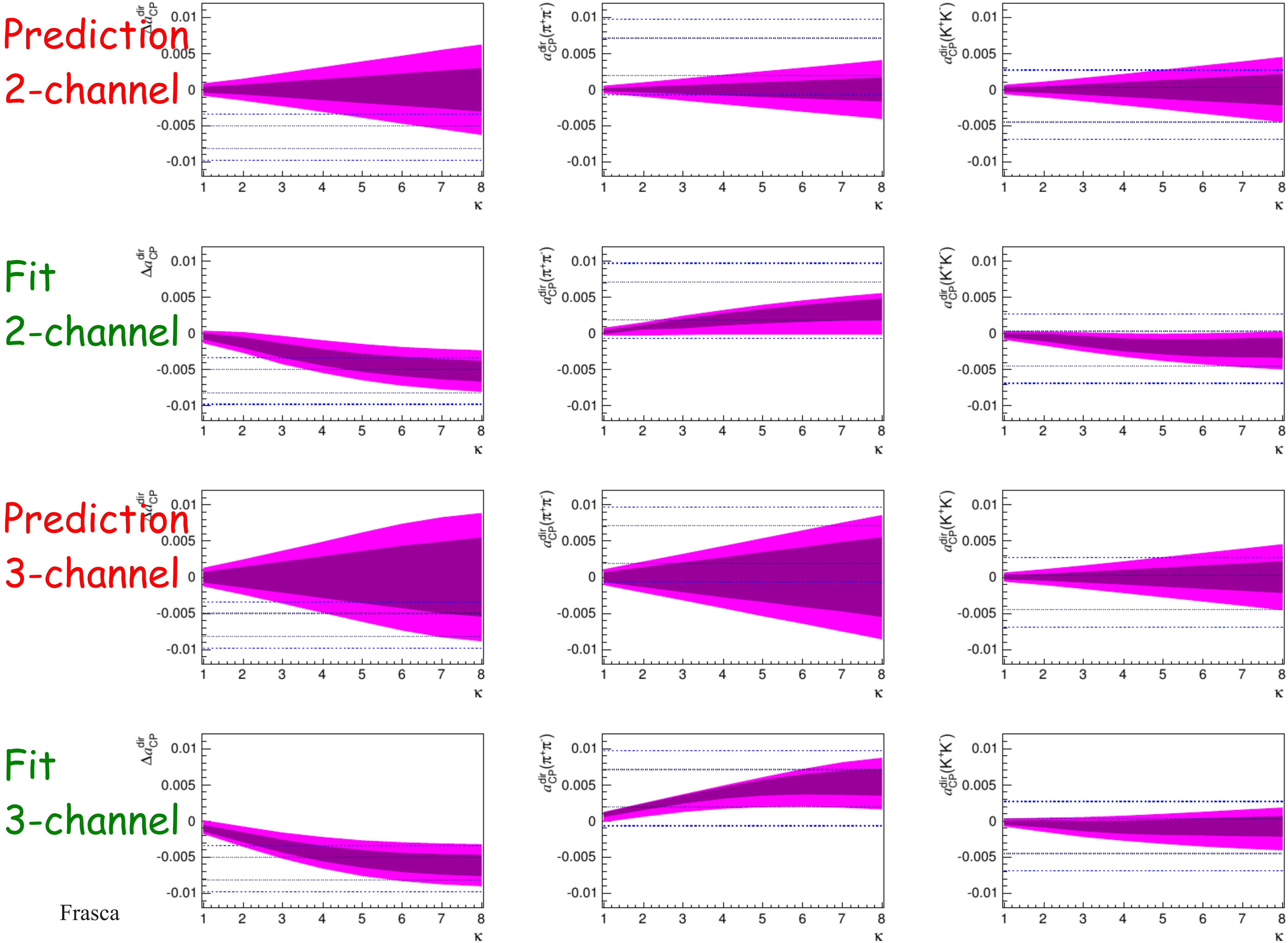
Fig. 3. Solution (– – –).

CP ASYMMETRIES

- One can study the CP asymmetries as a function of the upper bound on the size of CPV contributions in the two- and three-channel scenarios. We write

$$|\mathcal{B}_0^\pi| < \kappa |\mathcal{A}_0^\pi|\,,$$
$$|\mathcal{B}_0^K - \mathcal{A}_0^K| < \kappa |\mathcal{A}_0^K|\,,$$
$$|\mathcal{B}_{11}^K - (\mathcal{A}_{11}^K - \mathcal{A}_{13}^K)| < \kappa |\mathcal{A}_{11}^K - \mathcal{A}_{13}^K|\,,$$

  and consider predictions and fit results for CP asymmetries


Prediction
2-channel
Fit
2-channel
Prediction
3-channel
Fit
3-channel
Δa_{CP}^{dir}
$a_{CP}^{dir}(\pi^+\pi^-)$
$a_{CP}^{dir}(K^+K^-)$
0.01
0.005
0
-0.005
-0.01
1 2 3 4 5 6 7 8
κ
Frasca

CONCLUSIONS FROM UNITARITY

- The prediction does not reach the exp value within 2σ even for κ=8 in the 2-channel case
- Without unitarity constraints, the prediction reaches the exp value at the 2σ level for κ>5, but even for κ=8 it is still 1σ below
- How large can κ be?
  - translate fit results into RGI parameters
  - compare with K and B

FROM ISOSPIN AMPLITUDES TO RGI PARAMETERS

- The BR fit results can be translated into results for RGI parameters (aka topologies). Neglecting for simplicity $O(1/N_c^2)$ terms:

$$E_1(\pi) + E_2(\pi) = (1.72 \pm 0.04) \times 10^{-6}\, e^{i\delta}\ \text{GeV}\,,$$

$$E_1(\pi) + A_2(\pi) - P_1^{\text{GIM}}(\pi) = (2.10 \pm 0.02) \times 10^{-6}\, e^{i(\delta \pm (71\pm3)^\circ)}\ \text{GeV}\,,$$

$$E_2(\pi) - A_2(\pi) + P_1^{\text{GIM}}(\pi) = (2.25 \pm 0.07) \times 10^{-6}\, e^{i(\delta \mp (62\pm2)^\circ)}\ \text{GeV}$$

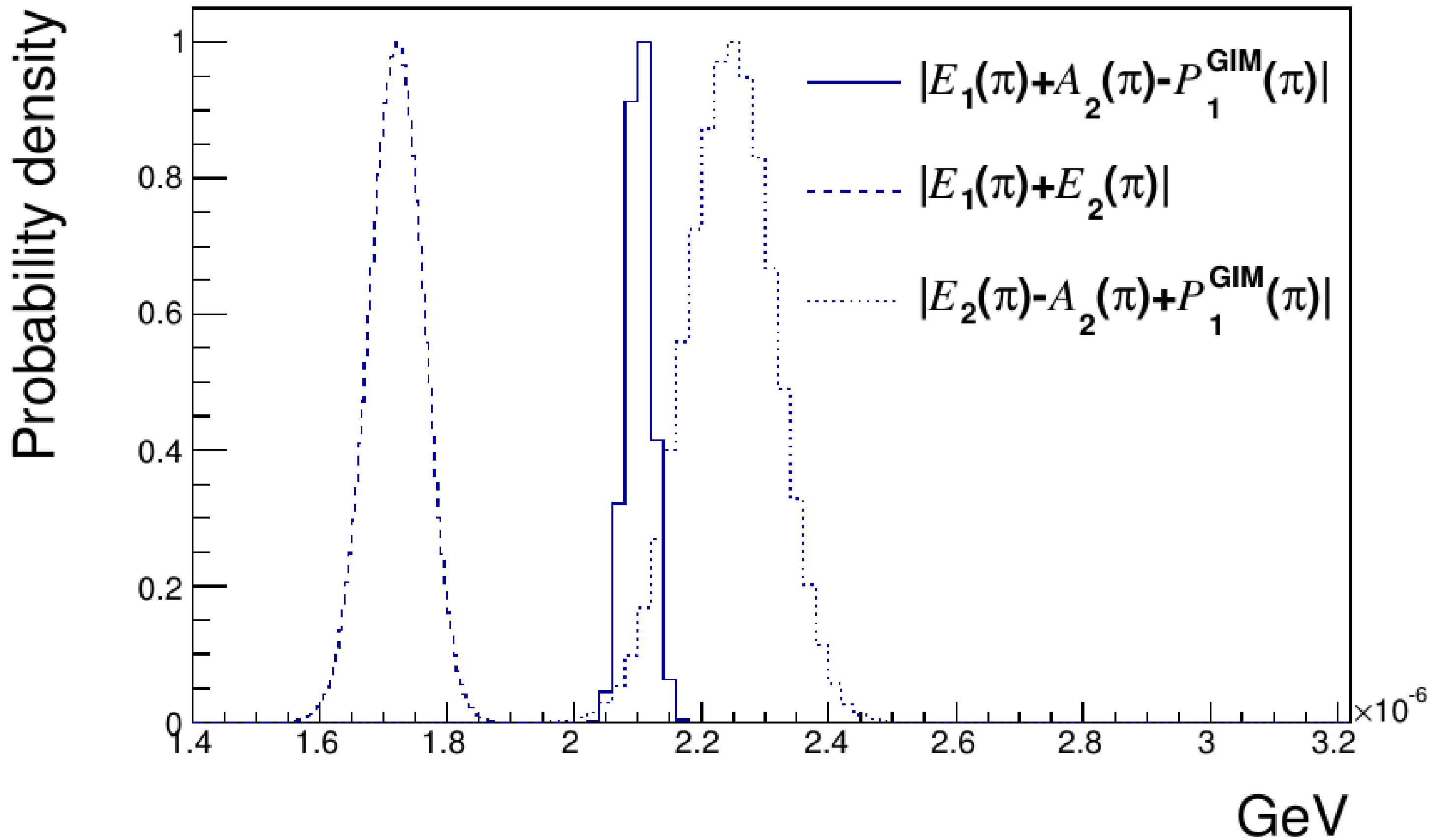
- E_1 does not dominate the amplitudes ⇒ we are away from the infinite mass limit
- All amplitudes of same size, w. large phases

THE MEANING OF κ

- The condition $|\mathcal{B}_0^\pi| < \kappa |\mathcal{A}_0^\pi|$, means

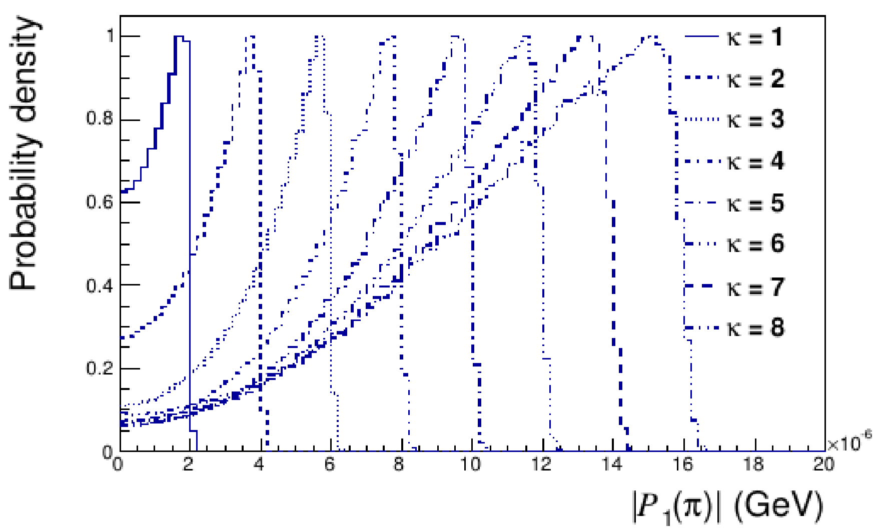
$$|P_1(\pi)| \leq \kappa \left| \frac{2}{3} E_1(\pi) - \frac{1}{3} E_2(\pi) + A_2(\pi) - P_1^{\rm GIM}(\pi) \right|$$

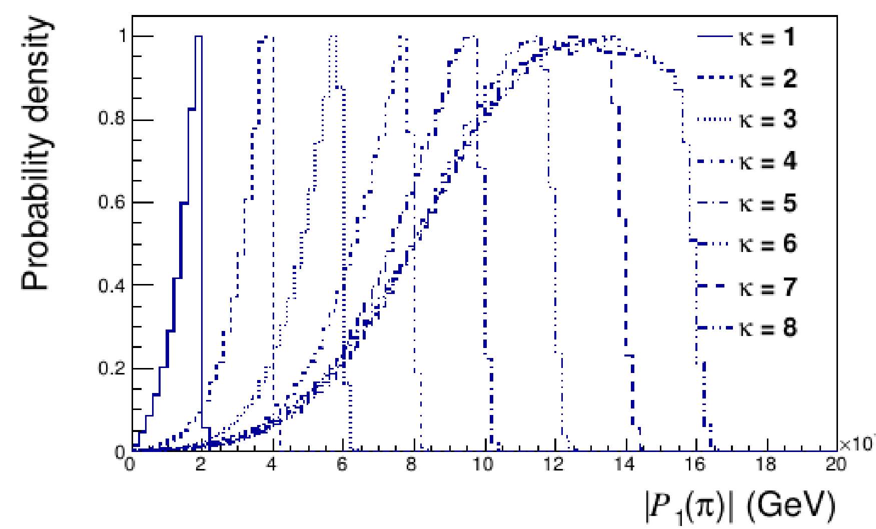
- κ is the ratio of $|P_1|$ over all other topologies
- Notice that $P_1 \sim P_b - P_s$ while $P_1^{GIM} \sim P_d - P_s$
- How large should $|P_1|$ be to reproduce Δa_{CP}^{dir}?



2-channel

3-channel





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DYNAMICAL ARGUMENTS

- The amplitudes for K, D and B $\to \pi\pi$ are formally the same, with the obvious flavour and CKM replacements.
- In the Kaon system, one has

$$(P_u - P_c) \sim 3\,(P_t - P_c) \sim 25\,(E_1 + E_2)$$

- No enhancement expected for P_u (will be checked on the lattice soon), while P_c and P_t generate local operators with chirally enhanced matrix elements (SVZ)

DYNAMICAL ARGUMENTS II

- In charm decays, no chiral enhancement is present, so that one expects

$$|P_1| = |P_b - P_s| \leq |E_1|, |E_2|, |A_1|, |A_2|, |P_1^{GIM}|$$

i.e. $\kappa \leq 1$.

- In B decays one is much closer to the infinite mass limit so that $|E_1|$ and $|E_2|$ dominate, with all other contractions power suppressed.

CONCLUSIONS

- The SM UTA has reached high precision and redundancy, allowing to test the SM and search for NP
- Overall picture consistent with the SM, with nonstandard CPV in $\Delta F=2$ possible at the few degrees level in all sectors
- Stringent bounds on the NP scale from $\Delta F=2$ processes

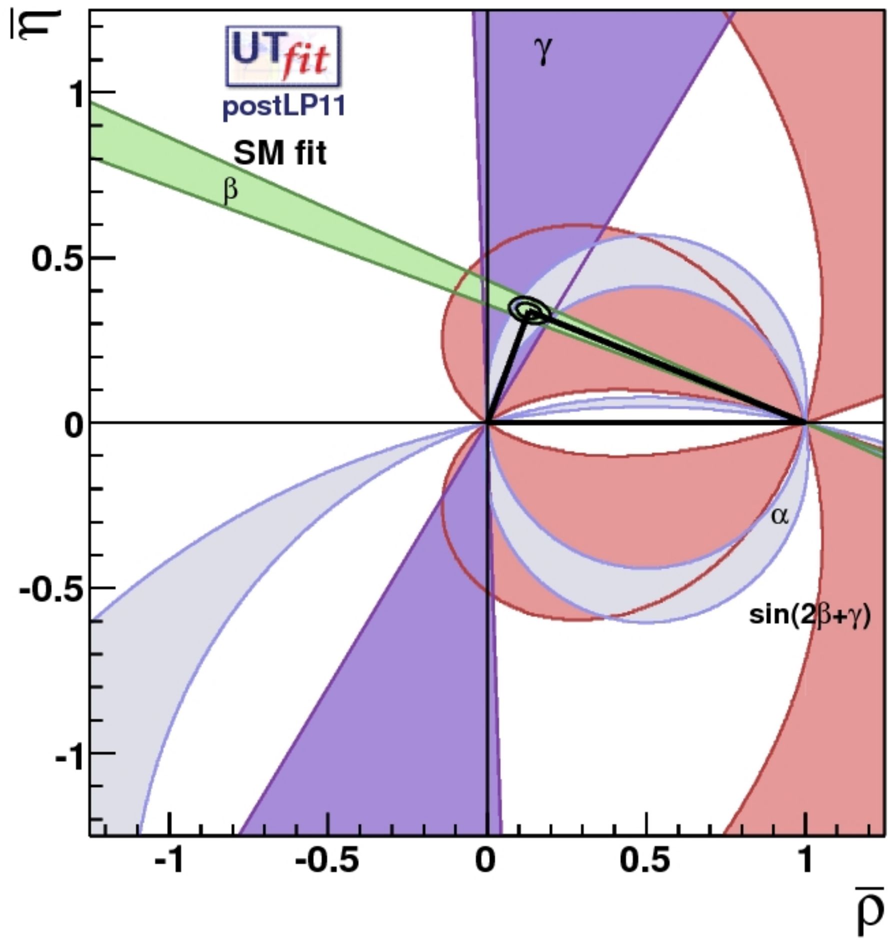
CONCLUSIONS II

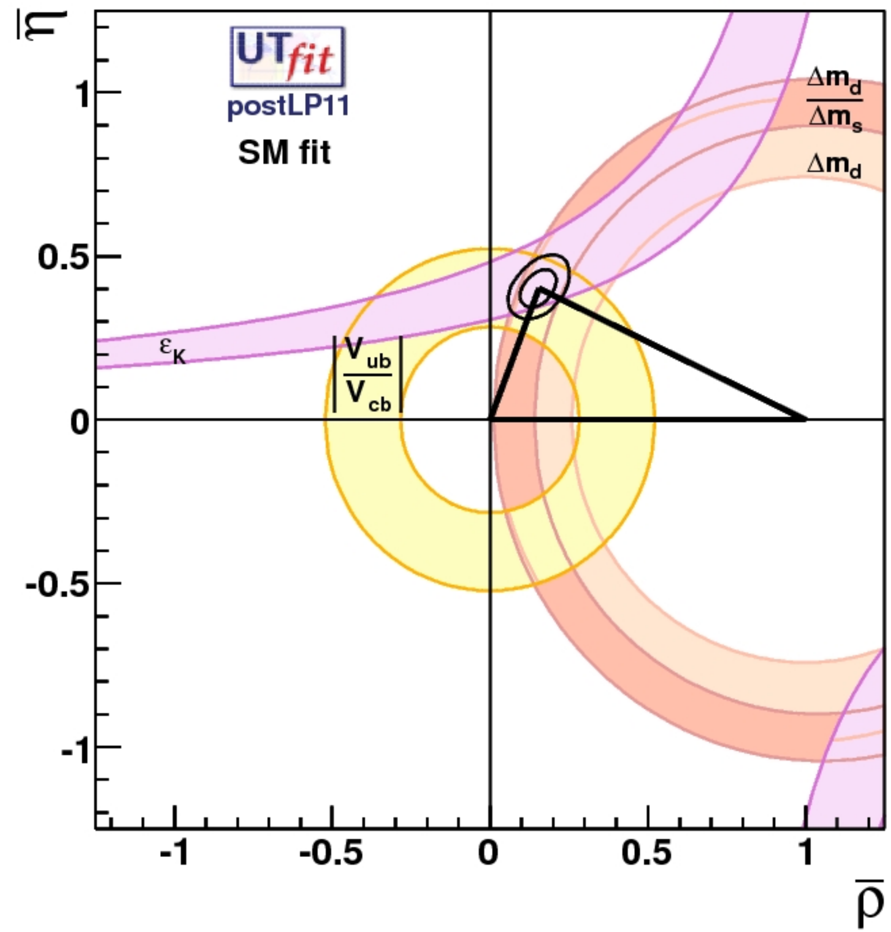
- However, looking more closely there are several (unexpected) deviations from the SM at the 2-3σ level: sin2β, $B \rightarrow (D^{(*)}) \tau \nu$, ΔA_{CP},...
- These deviations are not easily accommodated in simple NP models
- Direct searches are also telling us that simple NP models are unnatural
- Wait for more hints in the very near future!

BACKUP SLIDES

angles vs the others

levels @
95% Prob

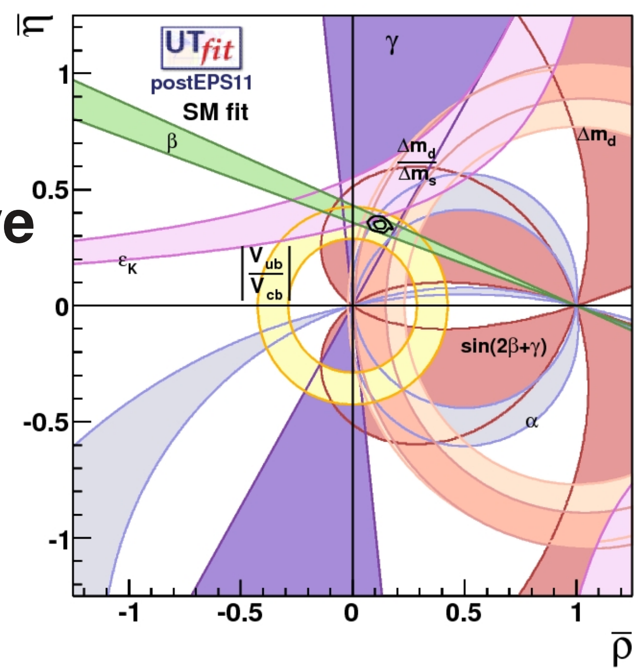




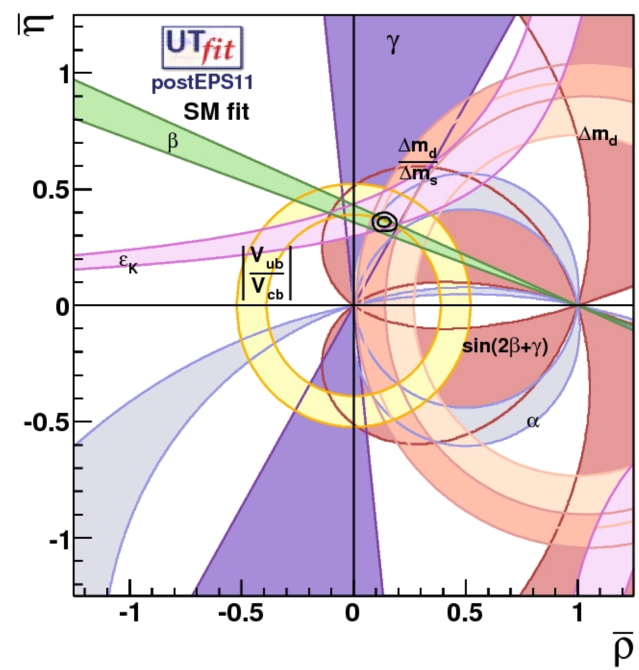
$\bar{\rho} = 0.130 \pm 0.027$
$\bar{\eta} = 0.338 \pm 0.016$

$\bar{\rho} = 0.154 \pm 0.038$
$\bar{\eta} = 0.400 \pm 0.038$

only exclusive values

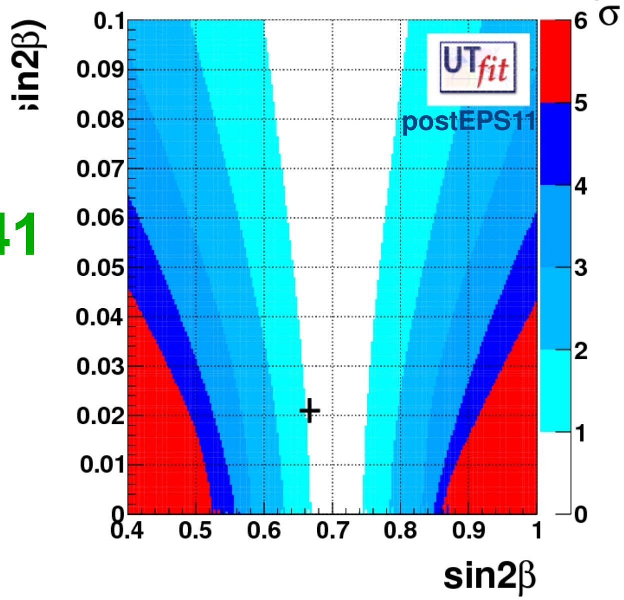


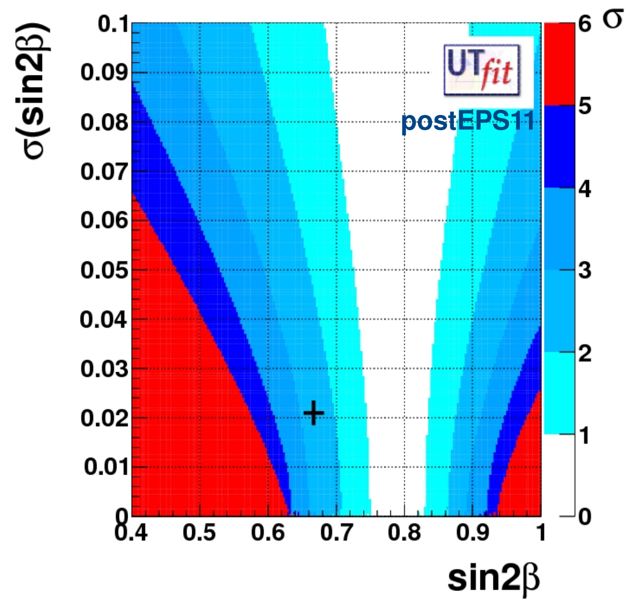
only inclusive values



$\sin 2\beta_{UTfit}$ = 0.706 ± 0.041

~0.8σ





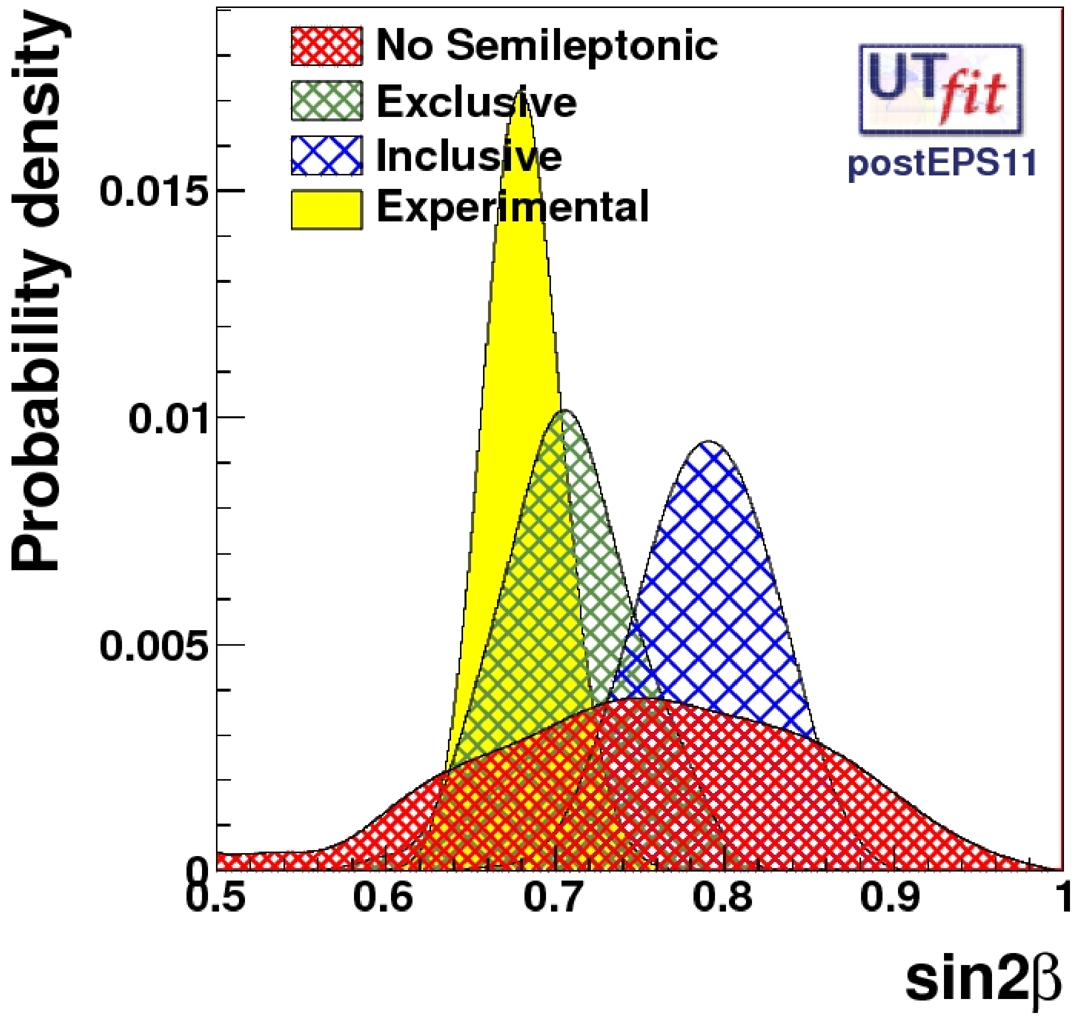
$\sin 2\beta_{UTfit}$ = 0.791 ± 0.041

~2.6σ

$\sin 2\beta_{UTfit}$ = 0.76 ± 0.10 ¬ *no semileptonic*

~0.9σ

inclusives vs exclusives



only exclusive values

$\sin 2\beta_{UTfit}$ = 0.706 ± 0.041

~0.8σ

only inclusive values

$\sin 2\beta_{UTfit}$ = 0.791 ± 0.041

~2.6σ

$\sin 2\beta_{UTfit}$ = 0.76 ± 0.10 ¬ *no semileptonic*

~0.9σ