Unitarity triangle fits: Standard model & Search for New Physics

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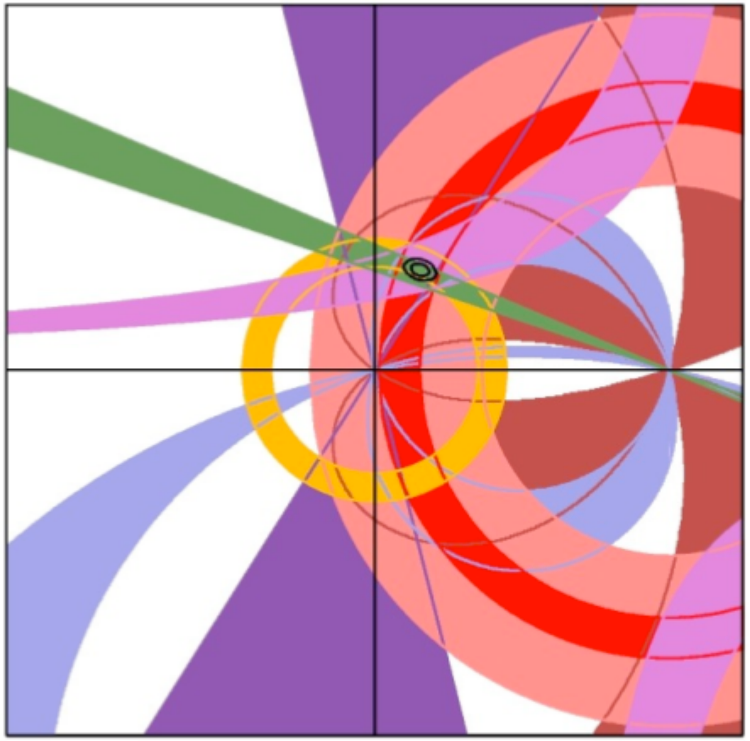
STANDARD MODEL UNITARITY TRIANGLE ANALYSIS (Flavor Physics)



- *Provides the best determination of the CKM parameters;*
- *Tests the consistency of the SM (``direct” vs ``indirect” determinations) @ the quantum level;*
- *Provides predictions for SM observables (in the past for example sin 2β and Δm_s)*
- *It could lead to new discoveries (CP violation, Charm, !?)*

Flavor physics in the Standard Model

In the SM, the quark mass matrix, from which the CKM matrix and ~~CP~~ violation originate, is determined by the coupling of the Higgs boson to fermions.

$$\mathcal{L}^{\text{quarks}} = \mathcal{L}^{\text{kinetic}} + \mathcal{L}^{\text{gauge}} + \mathcal{L}^{Yukawa}$$

CP invariant

~~CP~~ and symmetry breaking are striclty correlated

$$\mathcal{L}(\Lambda_{Fermi}) = \mathcal{L}(\Lambda, H, H^\dagger) + \mathcal{L}^{kin} + \mathcal{L}_{SM}^{gauge} + \mathcal{L}_{SM}^{Yukawa} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \dots$$

EWSB

has many accidental simmetries

may violate accidental simmetries

Absence of FCNC at tree level (& GIM suppression of FCNC @loop level)

Almost no CP violation at tree level

Flavour Physics is extremely sensitive to New Physics (NP)

WHY RARE DECAYS ?

Rare decays are a manifestation of broken (accidental) symmetries e.g. of physics beyond the Standard Model

Proton decay	**baryon and lepton number conservation**
$\mu \to e + \gamma$	**lepton flavor number**
$\nu_i \to \nu_k$	

RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC:

$q_i \to q_k + \nu \bar{\nu}$

$q_i \to q_k + l^+ l^-$

$q_i \to q_k + \gamma$

these decays occur only via loops because of GIM and are suppressed by CKM

THUS THEY ARE SENSITIVE TO
NEW PHYSICS

Why we like $K \to \pi \nu \bar{\nu}$?

For the same reason as $A_{J/\psi\, K_S}$:

1) Dominated by short distance dynamics

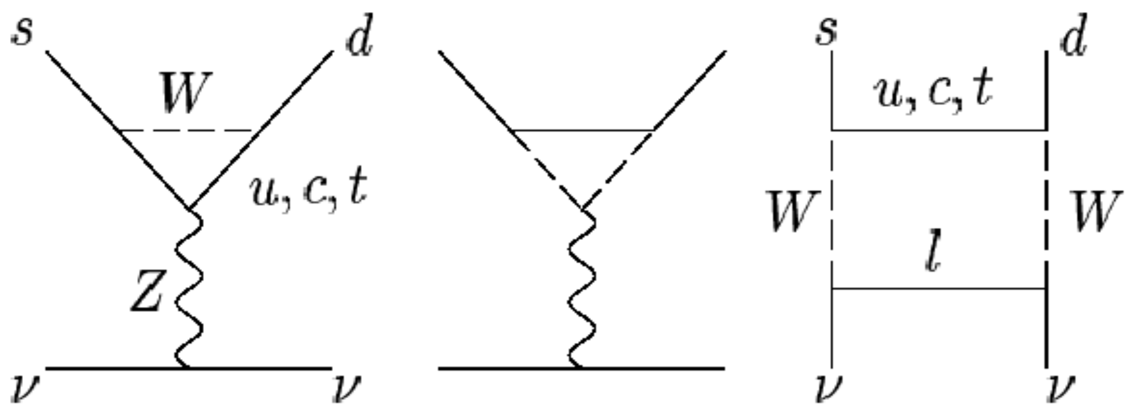
(hard GIM suppression, calculable in pert. theory)

2) **Negligible hadronic uncertainties**

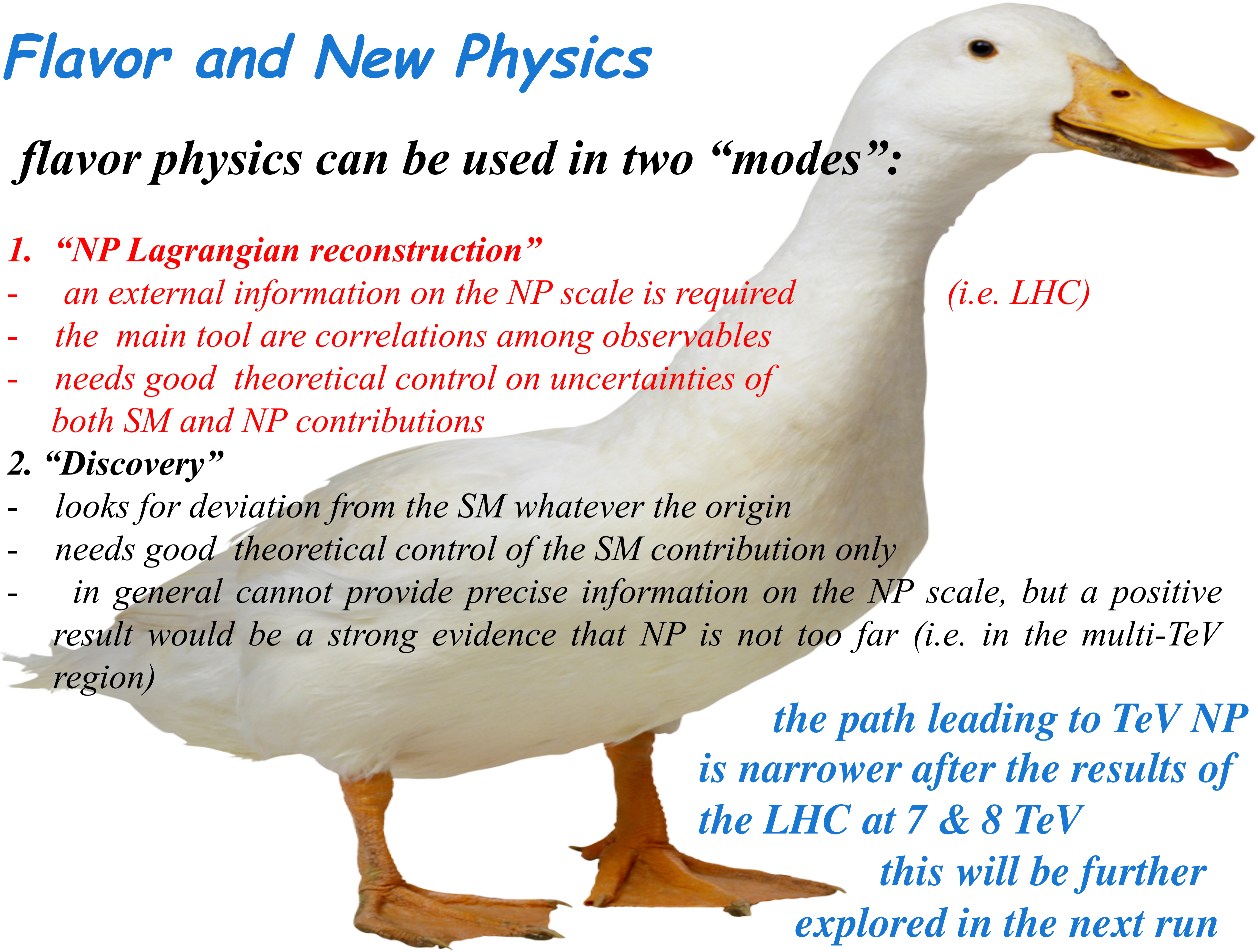
(matrix element known)

$O(G^2_F)$ Z and W penguin/box $s \to d\, \nu \bar{\nu}$ diagrams

SM Diagrams



Flavor and New Physics



flavor physics can be used in two "modes":

1. "NP Lagrangian reconstruction"

- *an external information on the NP scale is required* *(i.e. LHC)*
- *the main tool are correlations among observables*
- *needs good theoretical control on uncertainties of both SM and NP contributions*

2. "Discovery"

- *looks for deviation from the SM whatever the origin*
- *needs good theoretical control of the SM contribution only*
- *in general cannot provide precise information on the NP scale, but a positive result would be a strong evidence that NP is not too far (i.e. in the multi-TeV region)*

the path leading to TeV NP is narrower after the results of the LHC at 7 & 8 TeV

this will be further explored in the next run

CP Violation in the Standard Model

In the Standard Model the quark mass matrix, from which the CKM Matrix and $\cancel{CP}$ originate, is determined by the Yukawa Lagrangian which couples fermions and Higgs

$$\mathcal{L}^{\text{quarks}} = \mathcal{L}^{\text{kinetic}} + \mathcal{L}^{\text{weak int}} + \mathcal{L}^{\text{yukawa}}$$

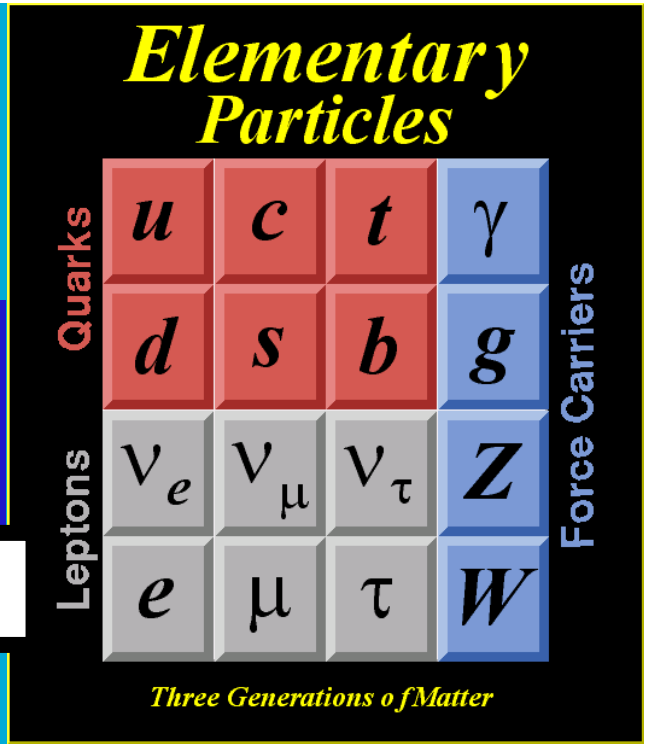
CP invariant

$\cancel{CP}$ and symmetry breaking are closely related !

QUARK MASSES ARE GENERATED BY DYNAMICAL SYMMETRY BREAKING

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad H^C = i\tau_2 H^*$$

$$\phi^+ \to 0 \qquad \phi^0 \to \frac{V}{\sqrt{2}}$$



Charge +2/3

$$\mathcal{L}^{\text{yukawa}} \equiv \Sigma_{i,k=1,N} [\, Y_{i,k} (q^i_L H^C) U^k_R + X_{i,k} (q^i_L H) D^k_R + \text{h.c.} \,]$$

Charge -1/3

$$\Sigma_{i,k=1,N} [\, m^u_{i,k} (\overline{u}^i_L u^k_R) + m^d_{i,k} (\overline{d}^i_L d^k_R) + \text{h.c.} \,]$$

Diagonalization of the Mass Matrix

Up to singular cases, the mass matrix can always be diagonalized by 2 unitary transformations

$u^i_L \to U^{ik}_L u^k_L \qquad u^i_R \to U^{ik}_R u^k_R$

$\mathbf{M'} = \mathbf{U^\dagger_L\ M\ U_R} \qquad \mathbf{(M')^\dagger = U^\dagger_R\ (M)^\dagger\ U_L}$

$$\mathcal{L}^{\mathbf{mass}} \equiv m_{\mathbf{up}}(\bar{u}_{\mathbf{L}} u_{\mathbf{R}} + \bar{u}_{\mathbf{R}} u_{\mathbf{L}}) + m_{\mathbf{ch}}(\bar{c}_{\mathbf{L}} c_{\mathbf{R}} + \bar{c}_{\mathbf{R}} c_{\mathbf{L}}) + m_{\mathbf{top}}(\bar{t}_{\mathbf{L}} t_{\mathbf{R}} + \bar{t}_{\mathbf{R}} t_{\mathbf{L}})$$

$$L_{CC}^{weak\,int} = \frac{g_W}{\sqrt{2}}(J_\mu^- W_\mu^+ + h.c.) \to \frac{g_W}{\sqrt{2}}(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W_\mu^+ + \ldots)$$

N(N-1)/2 angles and (N-1)(N-2) /2 phases

N=3 3 angles + 1 phase KM

the phase generates complex couplings i.e. <u>CP violation;</u>

6 masses +3 angles +1 phase = 10 parameters

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{tb}	V_{ts}	V_{tb}

NO Flavour Changing Neutral Currents (FCNC) at Tree Level
(FCNC processes are good candidates for observing NEW PHYSICS)

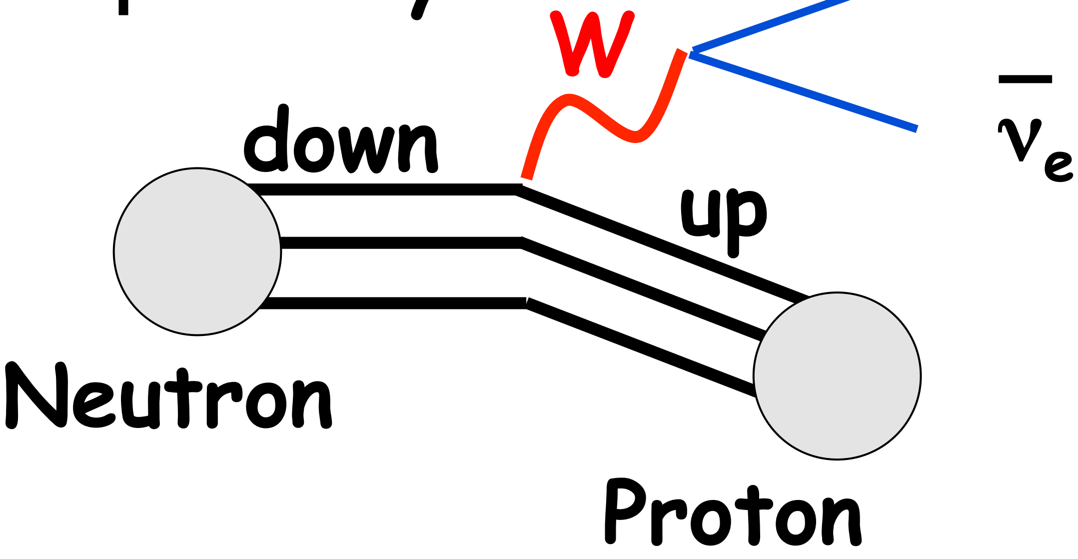
CP Violation is natural with three quark generations (Kobayashi-Maskawa)

With three generations all CP phenomena are related to the same unique parameter (δ)

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td}	V_{ts}	V_{tb}

Quark masses & Generation Mixing

β-decays



$| V_{ud} |$

$| V_{ud} | = 0.9735(8)$
$| V_{us} | = 0.2196(23)$
$| V_{cd} | = 0.224(16)$
$| V_{cs} | = 0.970(9)(70)$
$| V_{cb} | = 0.0406(8)$
$| V_{ub} | = 0.00409(25)$
$| V_{tb} | = 0.99(29)$
(0.999)

updated values later

Textures

There is a clear correlation between mixings and masses

$m_u \sim 4$ MeV $\quad m_c \sim 1200$ MeV $\quad m_t \sim 170$ GeV

$m_d \sim 8$ MeV $\quad m_s \sim 110$ MeV $\quad m_b \sim 4.3$ GeV

Orizontal $\mathcal{U}(2)$: $\psi_L \qquad \psi_L{}^c$

$$\mathcal{L}_{higgs} = Y\, H \left[\, (\psi_L{}^a)(\psi_L{}^b)^c\, S^{a\,b} + (\psi_L{}^a)(\psi_L{}^b)^c\, A^{a\,b} \,\right]$$

Symmetric tensor

Antisymmetric tensor

$$\sin\theta_c \sim \sqrt{m_d / m_s}$$

R.Gatto '70

$$M^d = M \begin{pmatrix} 0 & -\sqrt{x} \\ \sqrt{x} & 1+x \end{pmatrix}$$

$$\mathrm{diag}(M) = M\,(x\ ,\ 1)$$

$$x = m_d / m_s$$

$$V_1 = \begin{pmatrix} 1 \\ \sqrt{x} \end{pmatrix} \qquad \lambda_1 = M\,x$$

$$V_2 = \begin{pmatrix} -\sqrt{x} \\ 1 \end{pmatrix} \qquad \lambda_2 = M$$

Masses & Mixings (including the CP phases) are related !!

The Wolfenstein Parametrization

$1 - 1/2\,\lambda^2$	λ	$A\,\lambda^3(\rho - i\,\eta)$
$-\lambda$	$1 - 1/2\,\lambda^2$	$A\,\lambda^2$
$A\,\lambda^3 \times (1 - \rho - i\,\eta)$	$-A\,\lambda^2$	1

V_{ub}

$+ O(\lambda^4)$

V_{td}

$\sin\theta_{12} = \lambda$

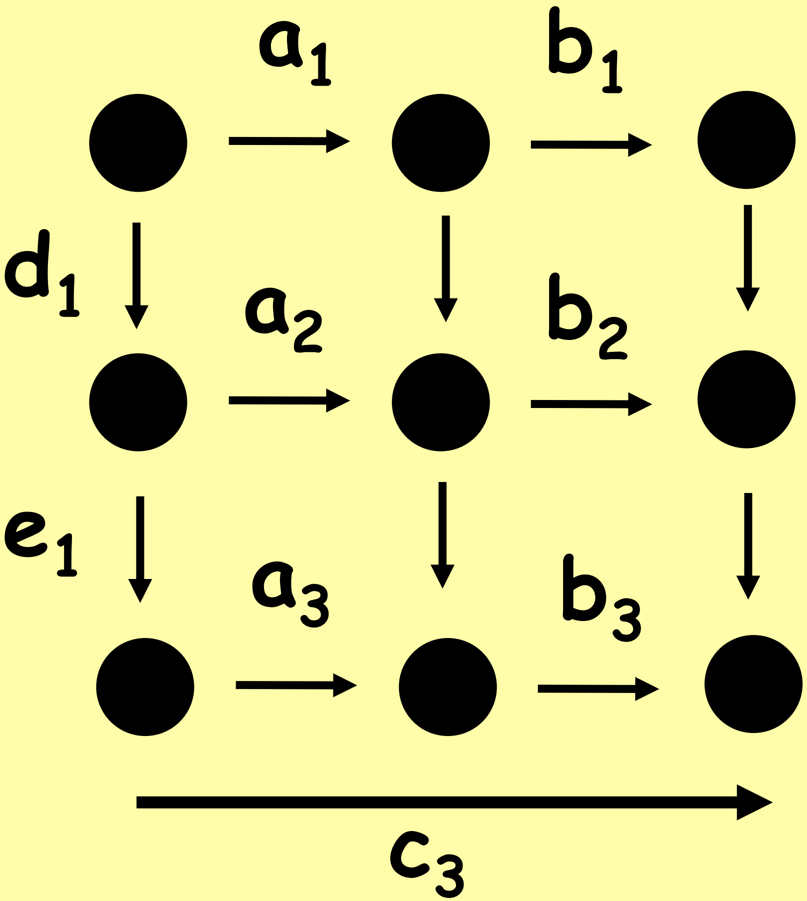
$\sin\theta_{23} = A\,\lambda^2$

$\sin\theta_{13} = A\,\lambda^3(\rho - i\,\eta)$

$\lambda \sim 0.2 \quad A \sim 0.8$

$\eta \sim 0.2 \quad \rho \sim 0.3$

The Bjorken-Jarlskog Unitarity Triangle

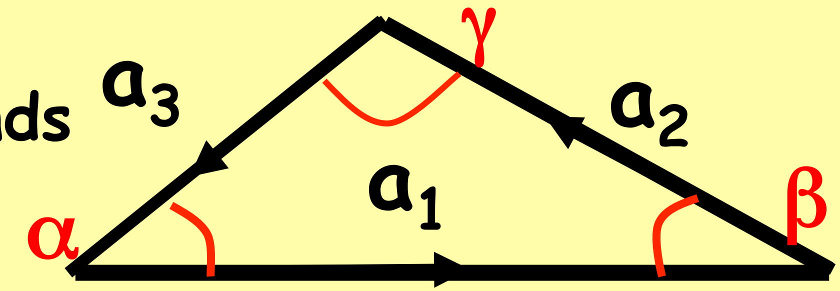


$|V_{ij}|$ is invariant under phase rotations

$$a_1 = V_{11} V_{12}^* = V_{ud} V_{us}^*$$
$$a_2 = V_{21} V_{22}^* \quad a_3 = V_{31} V_{32}^*$$

$$a_1 + a_2 + a_3 = 0$$
$$(b_1 + b_2 + b_3 = 0 \text{ etc.})$$

Only the orientation depends on the phase convention



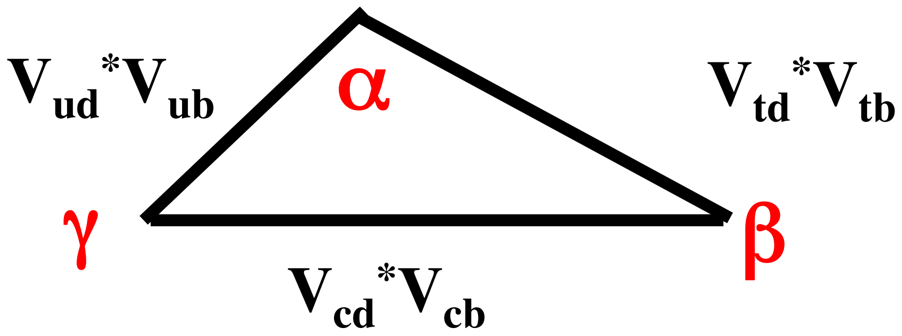
Physical quantities correspond to invariants under phase reparametrization i.e. $|a_1|, |a_2|, \ldots, |e_3|$ and the area of the Unitary Triangles

$$\boxed{J = \mathrm{Im}\,(a_1 a_2^*) = |a_1\, a_2|\, \mathrm{Sin}\,\beta}$$

a precise knowledge of the moduli (angles) would fix J

$$\cancel{CP} \propto J$$

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



$$\boxed{\gamma = \delta_{CKM}}$$

Gluons and quarks

The QCD Lagrangian :

$$L_{STRONG} = -1/4 \; G^{A}{}_{\mu\nu} G_{A}{}^{\mu\nu}$$ *GLUONS*

$$+ \sum_{f=flavour} \bar{q}_f \left(i \gamma_\mu D_\mu - m_f\right) q_f$$

QUARKS (& GLUONS)

$$G^{A}{}_{\mu\nu} = \partial_\mu G^{A}{}_{\nu} - \partial_{\nu} G^{A}{}_{\mu} - g_0 \; f^{ABC} G^{B}{}_{\mu} G^{C}{}_{\nu}$$

$$q_f \equiv q_f{}^{a}{}_{\alpha}(x) \qquad \gamma_\mu \equiv (\gamma_\mu)^{\alpha\beta} \qquad D_\mu \equiv \partial_\mu I + i \, g_0 \, t^{A}{}_{ab} \, G^{A}{}_{\mu}$$

STRONG CP VIOLATION

$$\mathcal{L}_\theta = \theta \, \tilde{G}^{\mu\nu a} G^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

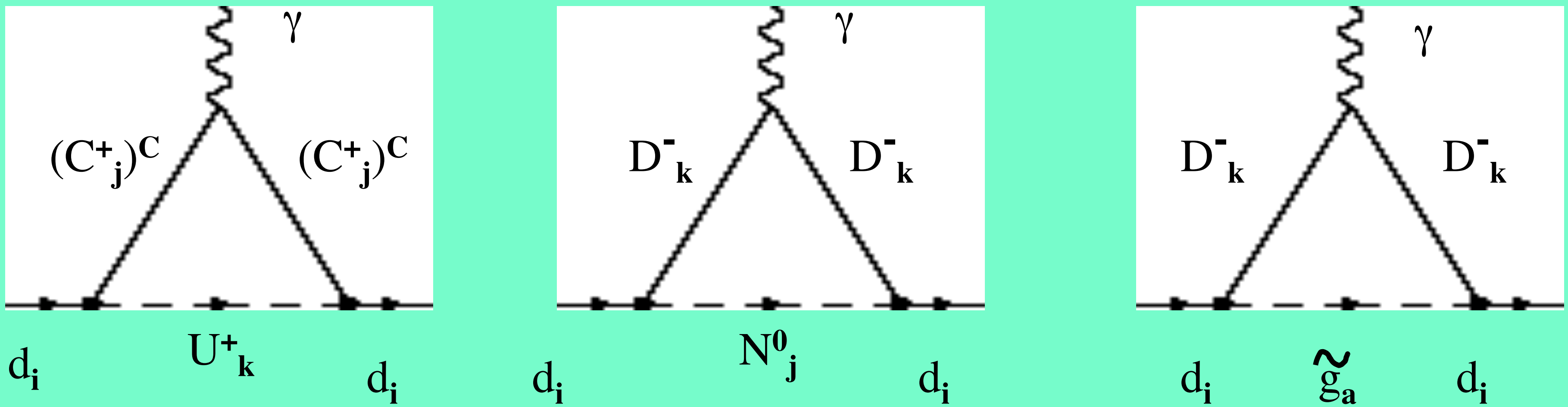
$$\mathcal{L}_\theta \sim \theta \, \vec{E}^a \cdot \vec{B}^a$$

This term violates CP and gives a contribution to the electric dipole moment of the neutron

$$e_n < 3 \; 10^{-26} \; e \; cm$$

$\theta < 10^{-10}$ which is quite unnatural !!

Neutron electric dipole moment in SuperSymmetry



$$\mathcal{L}^{\Delta F=0} = -i/2\, C_e\, \psi \sigma_{\mu\nu}\gamma_5 \psi\, F^{\mu\nu}$$
$$-i/2\, C_C\, \psi \sigma_{\mu\nu}\gamma_5\, t^a \psi\, G^{\mu\nu a}$$
$$-1/6\, C_g\, f_{abc}\, G^a{}_{\mu\rho}\, G^{b\rho}{}_{\nu}\, G^c{}_{\lambda\sigma}\, \varepsilon^{\mu\nu\lambda\sigma}$$

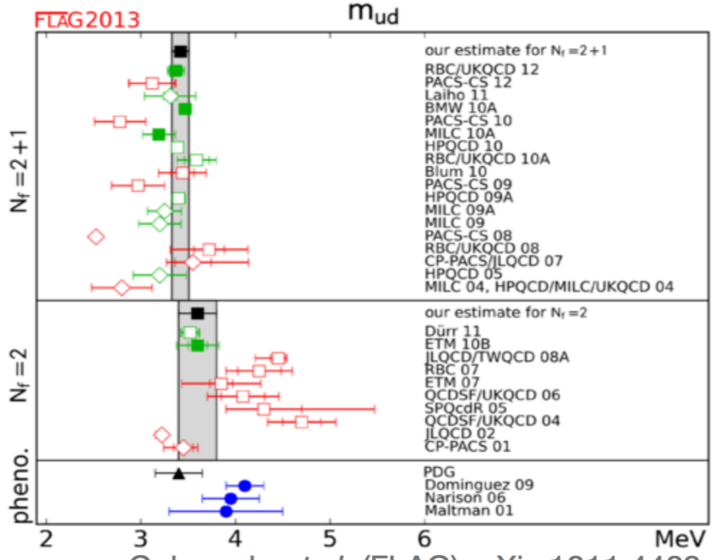
$C_{e,C,g}$ can be computed perturbatively

(Some) Resolutions of the Strong CP Problem

- Just declare CP to be good in the strong sector
  - Weak sector can reintroduce the problem

- $m_u = 0$ $$\bar{q}\left(i\not{D} - m e^{i\theta'\gamma_5}\right) q$$
  'τ Hooft PRL **37** 8 (1976)
  Jackiw & Rebbi, PRL **37** 127 (1976)
  Callan, Dashen & Gross PLB **63** 335 (1976)
  Kaplan & Manohar PRL **56** 2004 (1986)
  - $m_u \neq 0$
    Gasser & Leutwyler PhysRept **87** 77-169 (1982)

- Additional Peccei-Quinn symmetry & axions
  Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791



Colangelo *et al.* (FLAG) arXiv:1011.4408

$$m_u^{\overline{MS}}(2\,\mathrm{GeV}) = 2.40\,(15)(17)\mathrm{MeV}$$
$$m_d^{\overline{MS}}(2\,\mathrm{GeV}) = 4.80\,(15)(17)\mathrm{MeV}$$

RM123

$$\frac{m_u^{\overline{MS}}}{m_d^{\overline{MS}}} = 0.50\,(2)(3)$$

$$m_u^{\overline{MS}}(2\,\mathrm{GeV}) = 2.16\,(9)(7)\mathrm{MeV}$$

Flag

Axions

Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791

- Couple to topological charge

$$\mathcal{L}_{\text{axions}} = \frac{1}{2}(\partial_\mu a)^2 + \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

- Otherwise have shift symmetry.

$$a \to a + \alpha$$

- Amenable to effective theory treatment

$$V_{\text{eff}} \sim \cos\left(\theta + c\langle a \rangle\right)$$

$$m_a^2 f_a^2 = \chi$$

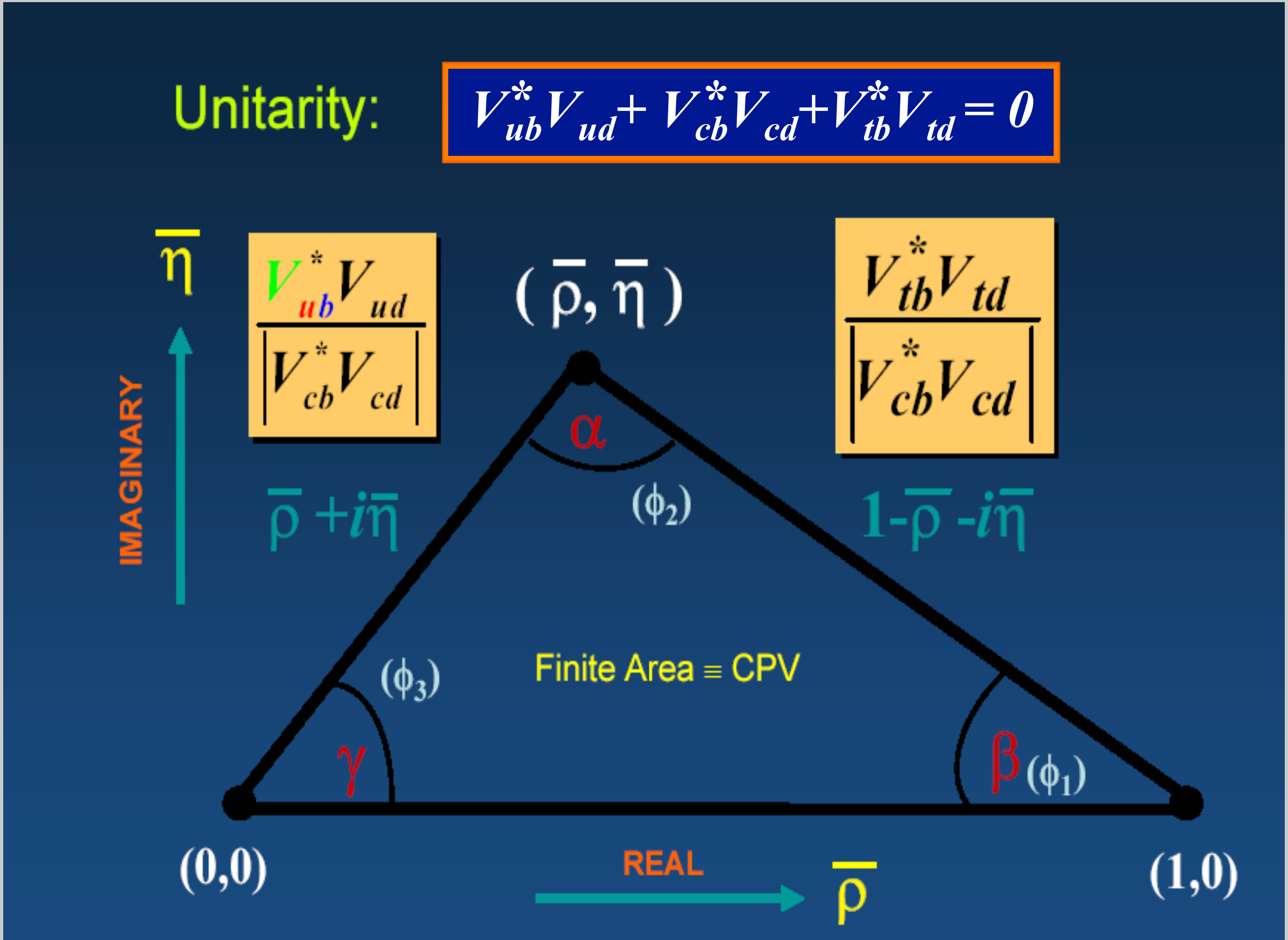
Axion mass

QCD Topological Susceptibility

- PQ symmetry can break before or after inflation.

Average over initial θ

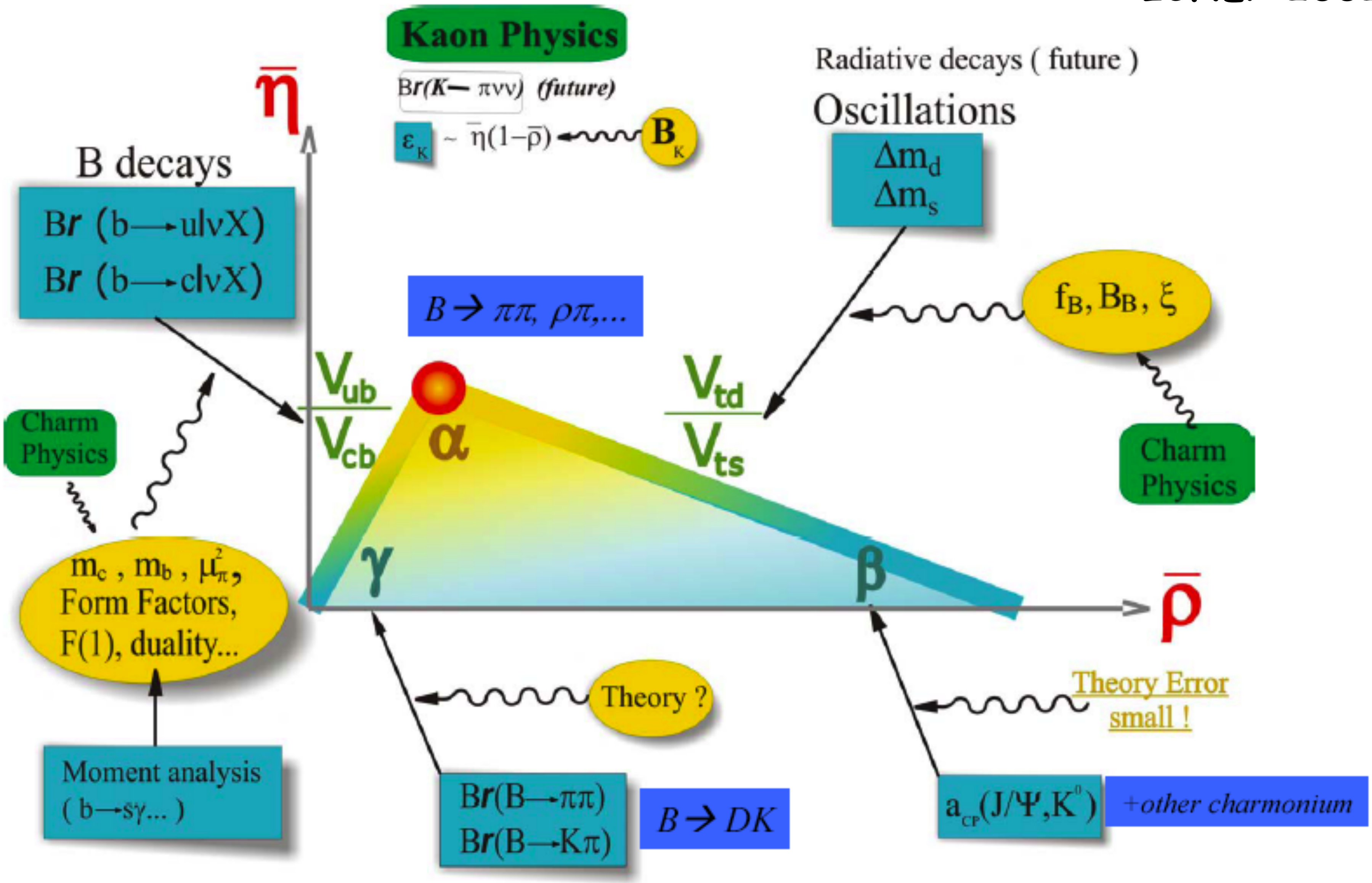
More this evening


Unitarity:
$V_{ub}^{*}V_{ud}+V_{cb}^{*}V_{cd}+V_{tb}^{*}V_{td}=0$
$\bar{\eta}$
IMAGINARY
$\frac{V_{ub}^{*}V_{ud}}{|V_{cb}^{*}V_{cd}|}$
$(\bar{\rho},\bar{\eta})$
$\frac{V_{tb}^{*}V_{td}}{|V_{cb}^{*}V_{cd}|}$
α
(ϕ_2)
$\bar{\rho}+i\bar{\eta}$
$1-\bar{\rho}-i\bar{\eta}$
(ϕ_3)
Finite Area ≡ CPV
γ
$\beta\,(\phi_1)$
(0,0)
REAL
$\bar{\rho}$
(1,0)

Visualization of the unitarity of the CKM matrix

Unitarity Triangle in the (ρ–η) plane

From
A. Stocchi
ICHEP 2002



Measure	V_{CKM}	Other NP parameters
$\Gamma(b \to u)/\Gamma(b \to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$\bar{\Lambda}, \lambda_1, F(1), \ldots$
ε_K	$\eta[(1-\bar{\rho}) + \ldots]$	B_K
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f_{B_d}^2 B_{B_d}$
$\Delta m_d / \Delta m_1$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
$A_{CP}(B_d \to J/\psi K_s)$	$\sin 2\beta$	$-$

$$Q^{EXP} = V_{CKM} \times \langle H_F | \hat{O} | H_I \rangle$$

For details see:
UTfit Collaboration

http://www.utfit.org

classical UT analysis

sin 2β is measured directly from $B \rightarrow J/\psi\, K_s$ decays at Babar & Belle & LHC

$$\mathcal{A}_{J/\psi\, K_s} = \frac{\Gamma(B_d^0 \rightarrow J/\psi\, K_s, t) - \Gamma(\bar{B}_d^0 \rightarrow J/\psi\, K_s, t)}{\Gamma(B_d^0 \rightarrow J/\psi\, K_s, t) + \Gamma(\bar{B}_d^0 \rightarrow J/\psi\, K_s, t)}$$

$$\boxed{\mathcal{A}_{J/\psi\, K_s} = \sin 2\beta \quad \sin(\Delta m_d t)}$$

DIFFERENT LEVELS OF THEORETICAL UNCERTAINTIES (STRONG INTERACTIONS)

1) First class quantities, with reduced or negligible theor. uncertainties

$A_{CP}(B \to J/\psi K_s)$ γ *from* $B \to DK$
$K^0 \to \pi^0 \nu \bar{\nu}$

2) Second class quantities, with theoretical errors of O(10%) or less that can be reliably estimated

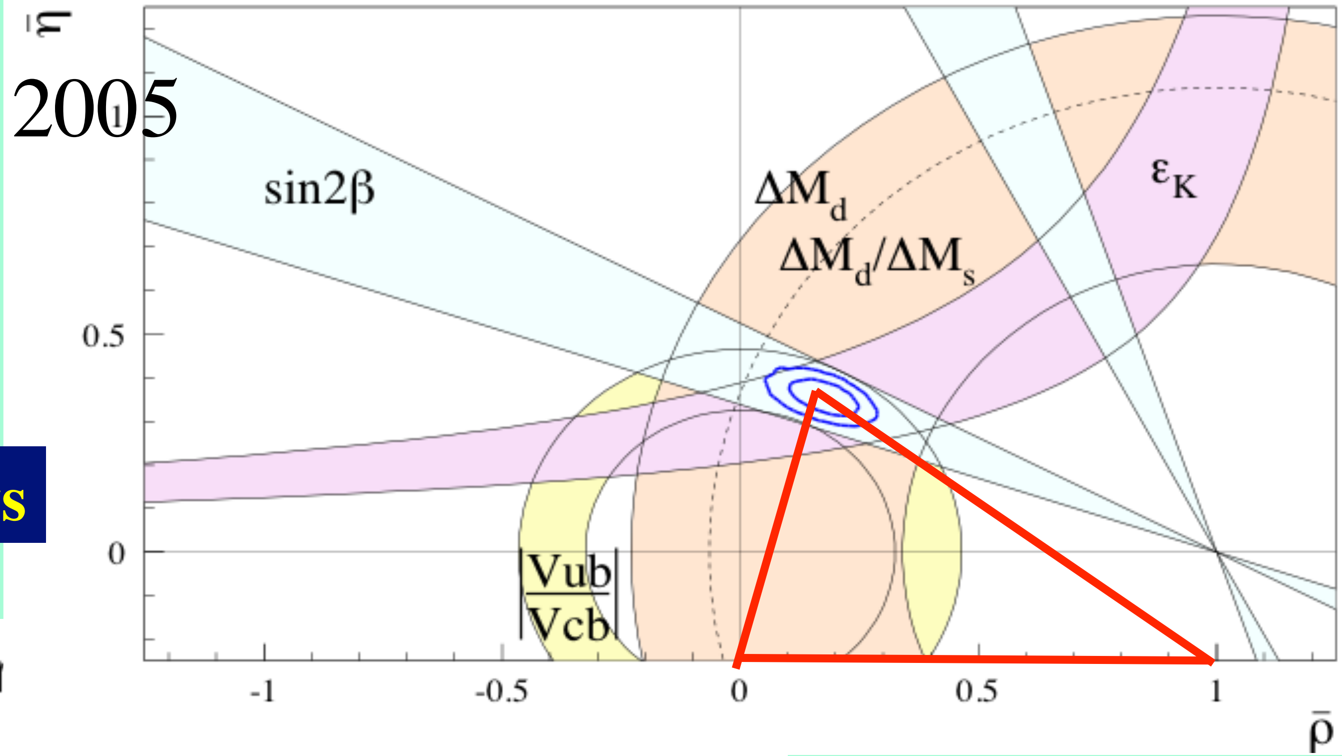
ε_K $\Delta M_{d,s}$
$\Gamma(B \to c, u)$, $K^+ \to \pi^+ \nu \bar{\nu}$

3) Third class quantities, for which theoretical predictions are model dependent (BBNS, charming, etc.)

In case of discrepacies we cannot tell whether is *new physics or we must blame the model*

$B \to K \pi$ $B \to \pi^0 \pi^0$
$B \to \phi K_s$

Unitary Triangle SM



semileptonic decays

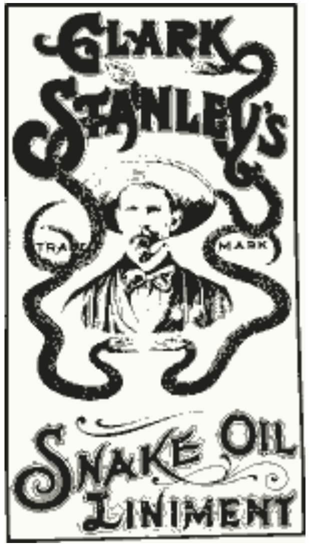
Experimental co

Meas.	$V_{CKM}\times$other	$(\bar{\rho}, \bar{\eta})$
$\frac{b\to u}{b\to c}$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar{\rho}^2+\bar{\eta}^2$
Δm_d	$\lvert V_{td}\rvert^2 f^2_{B_d} B_{B_d}$	$(1-\bar{\rho})^2+\bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert^2 \xi^2$	$(1-\bar{\rho})^2+\bar{\eta}^2$
ϵ_K	$f(A,\bar{\eta},\bar{\rho},B_K)$	$\propto \bar{\eta}(1-\bar{\rho})$
$A(J/\psi K^0)$	$sin2\beta$	$\frac{2\bar{\eta}(1-\bar{\rho})}{\sqrt{\bar{\eta}^2+(1-\bar{\rho})^2}}$

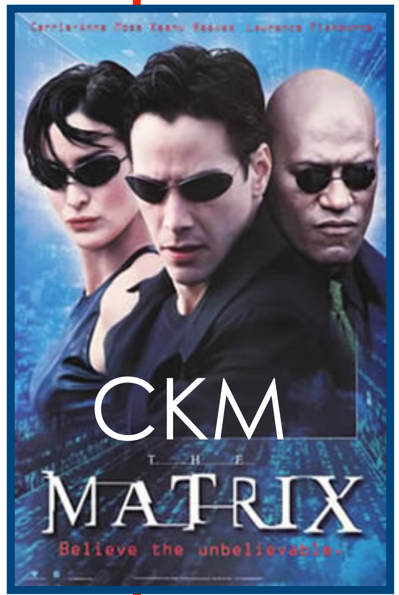
K^0 - $\overline{K}^0$ mixing

$B^0_{d,s}$ - $\overline{B}^0_{d,s}$ mixing

B_d Asymmetry



UTfit



M.Bona *et al.*, UTfit
JHEP0507:028, 2005

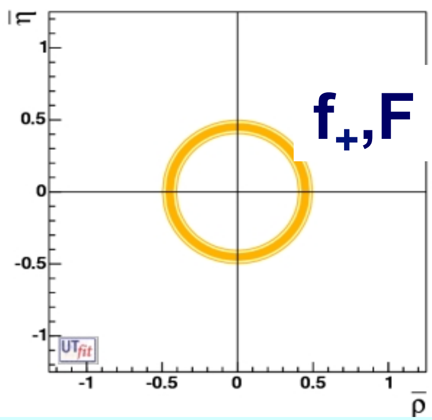
www.utfit.org

A. Bevan, M. Bona, M. Ciuchini,
D. Derkach, E. Franco, V. Lubicz,
G. Martinelli, F. Parodi, M. Pierini,
C. Schiavi, L. Silvestrini, A. Stocchi,
V. Sordini, C. Tarantino and V. Vagnoni

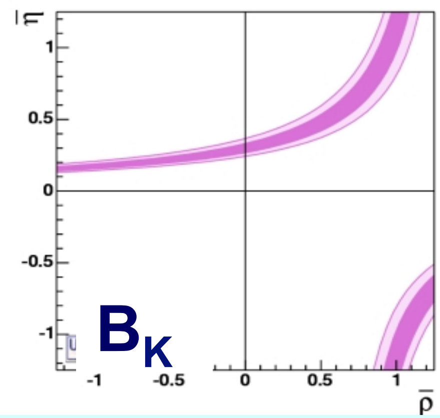
Quantities used in the Standard UT Analysis

levels @
68% (95%) CL

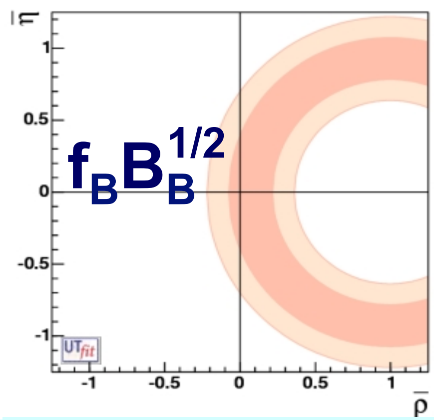
V_{ub}/V_{cb}



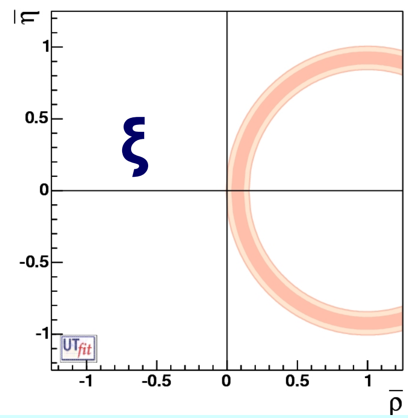
ε_K



Δm_d



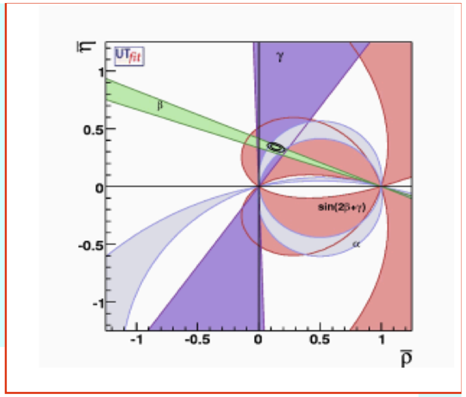
$\Delta m_d/\Delta m_s$



Inclusive vs Exclusive
Opportunity for lattice QCD

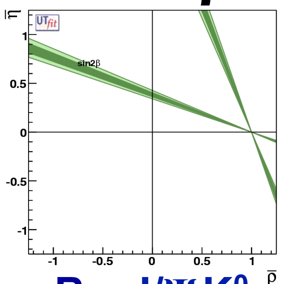
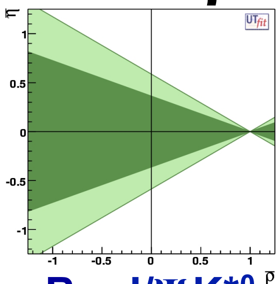
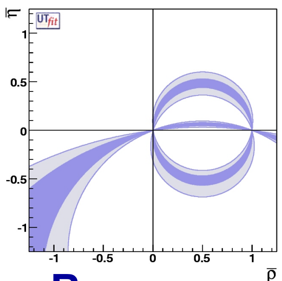
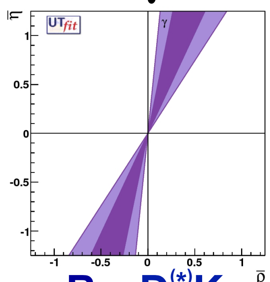
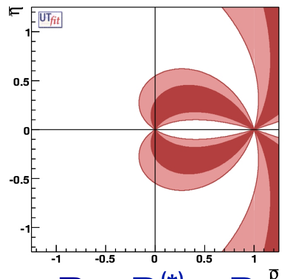
UT-LATTICE

Other Quantities used in the UT Analysis



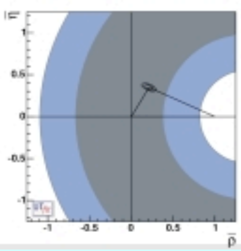
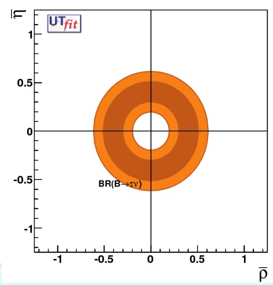
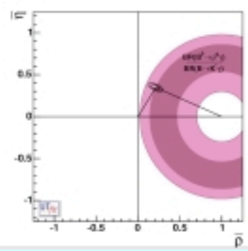
UT-ANGLES

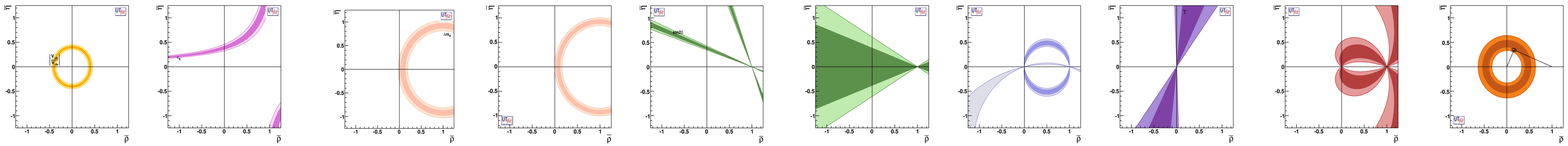
Several new determinations of UT angles are now available, thanks to the results coming from the B-Factory experiments

$\sin 2\beta$	$\cos 2\beta$	α	γ	$\sin(2\beta+\gamma)$
				
$B \to J/\Psi K^0$	$B \to J/\Psi K^{*0}$	$B \to \pi\pi, \rho\rho$	$B \to D^{(*)}K$	$B \to D^{(*)}\pi, D\rho$

New Constraints from B and K rare decays (not used yet)

New bounds are available from rare B and K decays. They do not still have a strong impact on the global fit and they are not used at present.

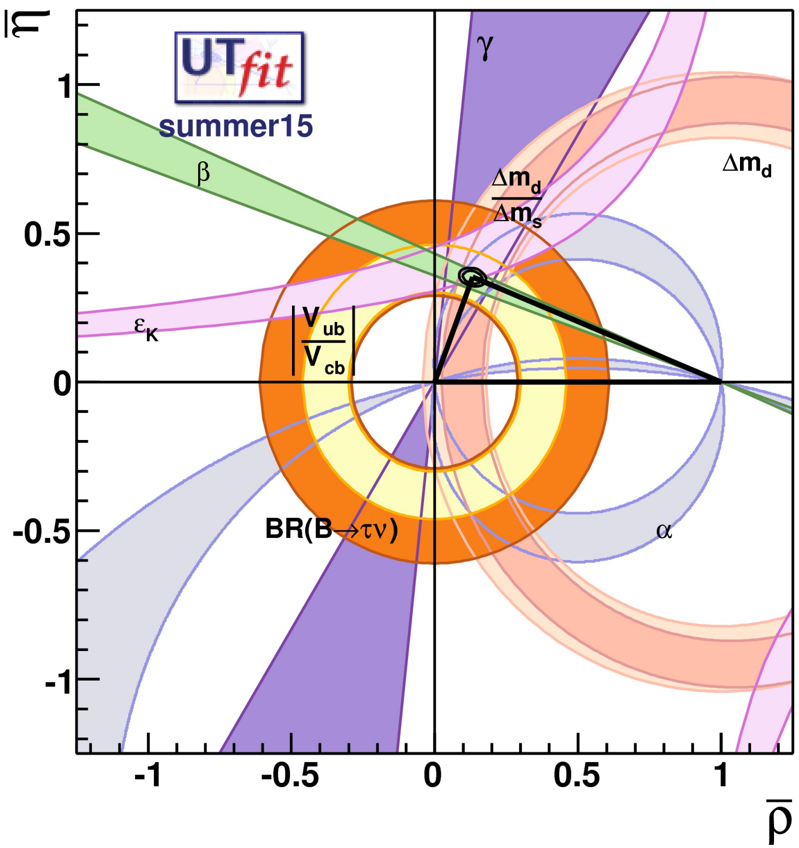
$K \to \pi \nu \bar{\nu}$	$B \to \tau \nu$	$(B \to \rho/\omega\, \gamma)/(B \to K^* \gamma)$
		



2015 results

$\bar{\rho} = 0.142 \pm 0.019$ $\bar{\eta} = 0.348 \pm 0.013$

In the hadronic sector, the SM CKM pattern represents the principal part of the flavor structure and of CP violation



$\alpha = (90.5 \pm 2.6)^0$

$\sin 2\beta = 0.691 \pm 0.018$

$\beta = (21.82 \pm 0.72)^0$

$\gamma = (67.4 \pm 2.7)^0$

$A = 0.828 \pm 0.012$

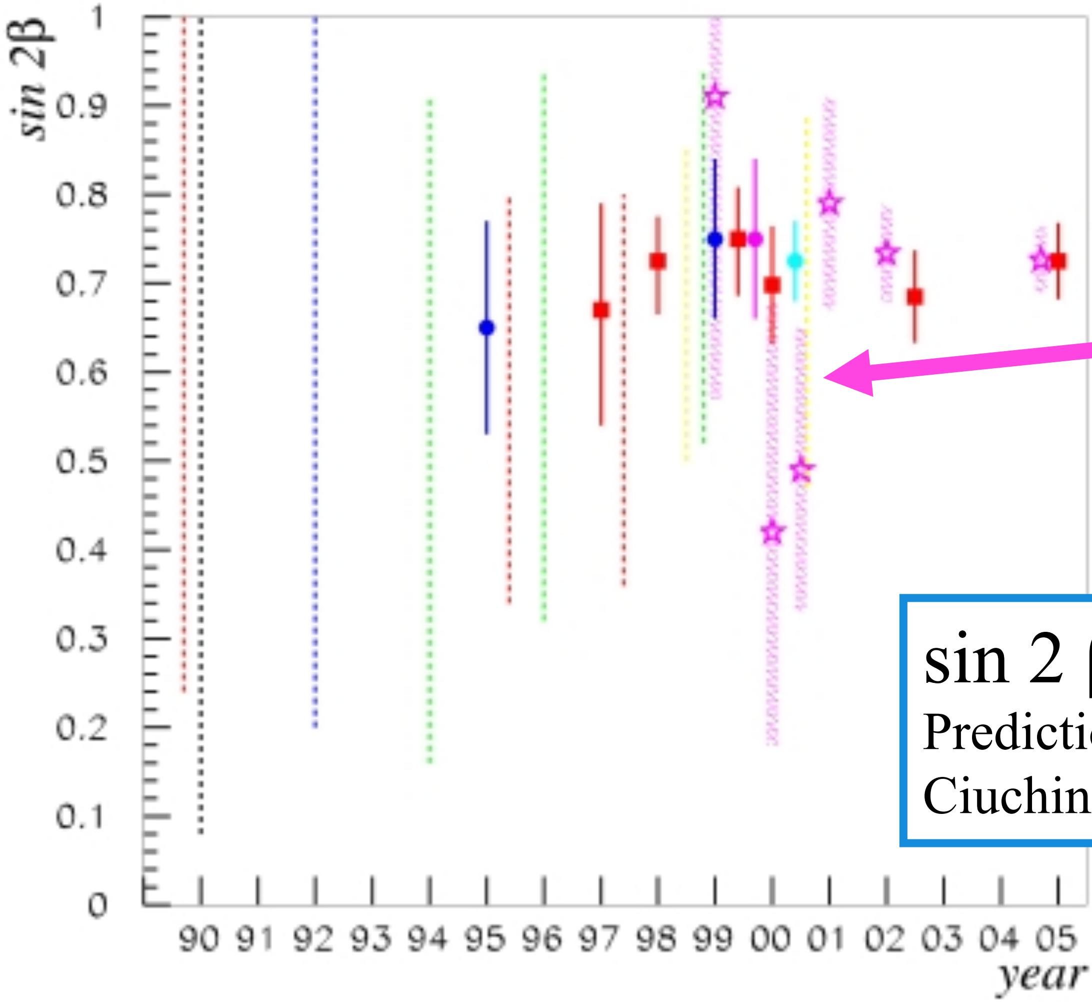
$\lambda = 0.22549 \pm 0.00066$

Consistence on an over constrained fit of the CKM parameters

CKM matrix is the dominant source of flavour mixing and CP violation

Theoretical predictions of Sin 2 β in the years

predictions exist since '95

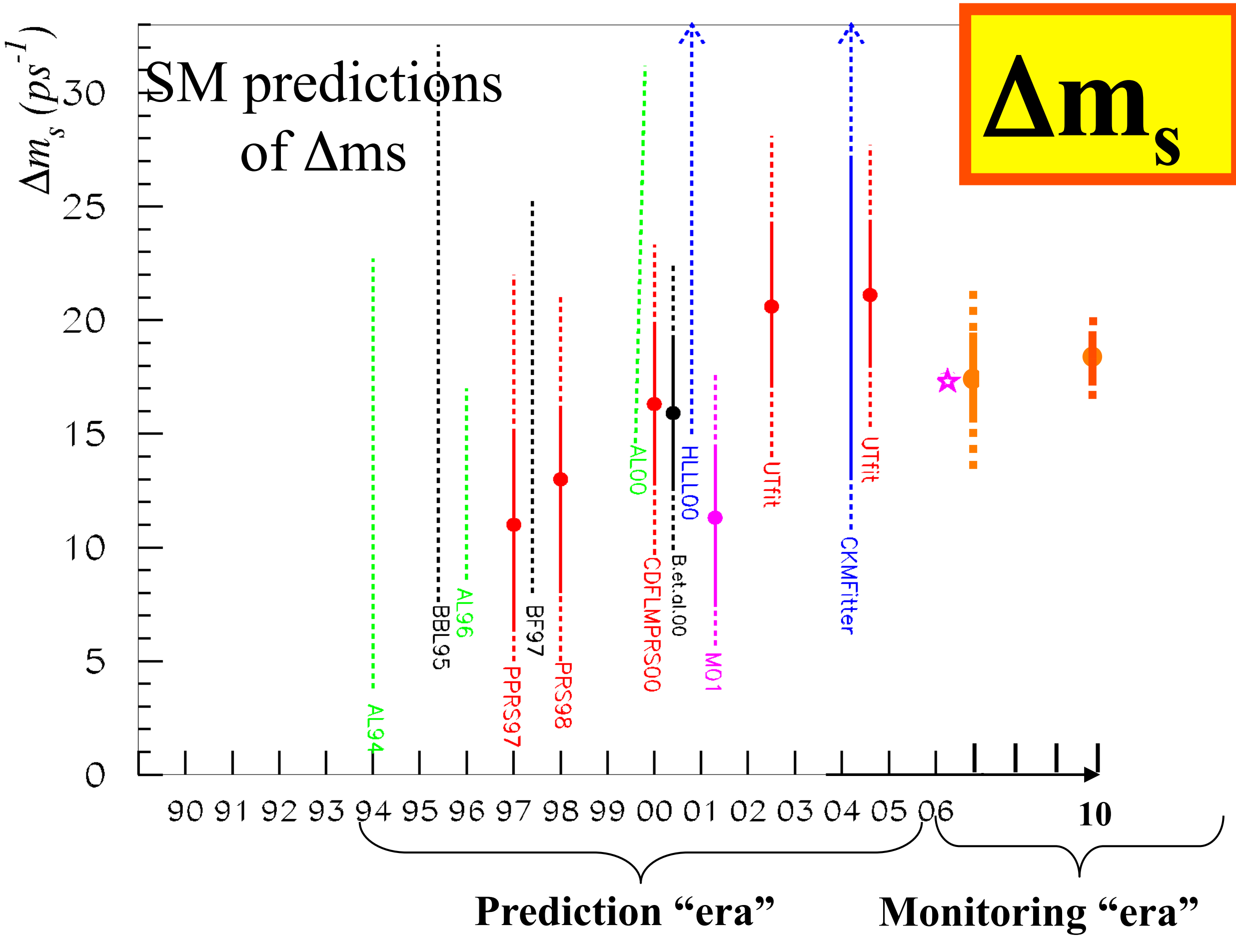


experiments

$\sin 2\beta_{UTA} = 0.65 \pm 0.12$

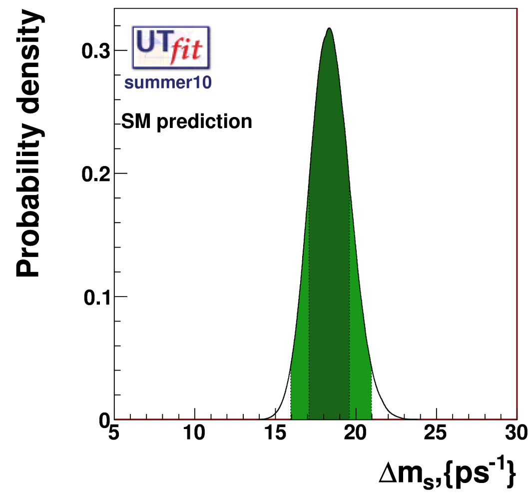
Prediction 1995 from Ciuchini,Franco,G.M.,Reina,Silvestrini

Δm_s



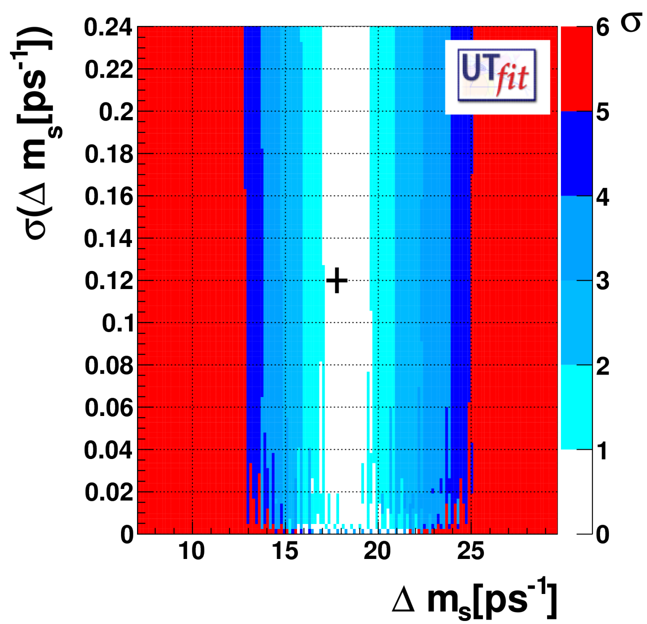
SM expectation

$\Delta m_s = (18.3 \pm 1.3\ )\ ps^{-1}$



Exp

$\Delta m_s = (17.77 \pm 0.12\ \ )\ ps^{-1}$



Legenda

agreement between the predicted values and the measurements at better than :

1σ 3σ 5σ

2σ 4σ 6σ

CKM-TRIANGLE ANALYSIS

State of The Art 2015

	Measurement	Fit	Prediction	Pull
α	$(92.7 \pm 6.2)^o$ 6.7 %	$(90.1 \pm 2.7)^o$ 2.9 %	$(88.3 \pm 3.4)^o$ 3.8 %	0.6
$\sin 2\beta$	0.680 ± 0.024 3.5 %	0.696 ± 0.022 2.6 %	0.747 ± 0.039 5.2 %	1.8
γ	$(71.4 \pm 6.5)^o$ 9.1 %	$(67.4 \pm 2.8)^o$ 4.2 %	$(66.7 \pm 3.0)^o$ 4.5 %	0.7
$\|V_{ub}\| \times 10^3$	3.81 ± 0.40 10 %	3.66 ± 0.12 3.3 %	3.64 ± 0.12 3.3 %	0.5
$\|V_{cb}\| \times 10^2$	4.09 ± 0.11 2.6 %	4.206 ± 0.053 1.2 %	4.240 ± 0.062 1.4 %	0.9
$\varepsilon_K \times 10^3$	2.228 ± 0.011 0.5 %	2.227 ± 0.011 0.5 %	2.08 ± 0.18 8.7 %	0.8
Δm_s (ps^{-1})	17.761 ± 0.022 0.1 %	17.755 ± 0.022 0.1 %	17.3 ± 1.0 5.7 %	0.2
$BR(B \to \tau\nu)\ \times 10^4$	1.06 ± 0.20 18.9 %	0.83 ± 0.07 7.9 %	0.81 ± 0.7 8.2 %	1.3
$\bar{B}R(B_s \to \mu\mu)\ \times 10^9$	2.9 ± 0.7 24.1 %	3.90 ± 0.15 3.8 %	3.94 ± 0.16 4.0 %	1.5 ew corrections not included
$BR(B_d \to \mu\mu)\ \times 10^9$	0.39 ± 0.15 38.5 %	0.1098 ± 0.0057 5.2 %	0.1103 ± 0.0058 5.2 %	1.9 ew corrections not included
β_s	$(0.97 \pm 0.95)^o$ 98 %	$(1.056 \pm 0.039)^o$ 4.4 %	$(1.056 \pm 0.039)^o$ 4.1 %	0.1 not included in the fit

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

LATTICE PARAMETERS

	Lattice	Prediction	Pull
$\hat{B}_K$	0.766 ± 0.010 1.3 %	0.84 ± 0.07 8.3 %	0.9
f_{B_s}	0.226 ± 0.005 2.2 %	0.2256 ± 0.0039 2.7 %	0.0
f_{B_s}/f_{B_d}	1.204 ± 0.016 1.3 %	1.197 ± 0.056 0.4 %	0.0
B_s	0.875 ± 0.040 1.3 %	0.875 ± 0.030 0.4 %	0.0
B_s/B_d	1.03 ± 0.08 7.8 %	1.096 ± 0.062 5.7 %	0.7

CKM Matrix in the SM

The fit results for all the nine CKM elements are

$$V_{CKM} = \begin{pmatrix} (0.9743 \pm 0.00014) & (0.22509 \pm 0.00061) & (0.00366 \pm 0.00012) e^{i(-67.8 \pm 2.8)^\circ} \\ (-0.22498 \pm 0.00066) e^{i(0.0353 \pm 0.00095)^\circ} & (0.97343 \pm 0.00015) e^{i(-0.00188333 \pm 5 \times 10^{-5})^\circ} & (0.04206 \pm 0.00053) \\ (0.00876 \pm 0.00015) e^{i(-22.03 \pm 0.83)^\circ} & (-0.04129 \pm 0.00054) e^{i(1.054 \pm 0.039)^\circ} & (0.999107 \pm 2.235 \times 10^{-5}) \end{pmatrix}$$

Standard Parametrization (PDG)

$\sin\theta_{12} = 0.22504 \pm 0.00065$

$\sin\theta_{23} = 0.04206 \pm 0.00054$

$\sin\theta_{13} = 0.00366 \pm 0.00012$ $\delta = 67.8 \pm 2.8$

Wolfenstein Parametrization (PDG)

$\lambda = 0.22514 \pm 0.00066$ $A = 0.828 \pm 0.0.12$

inclusives **vs** **exclusives**

	inclusives	exclusives
V_{ub}	$(4.41 \pm 0.22) \times 10^{-3}$	$(3.69 \pm 0.15) \times 10^{-3}$
V_{cb}	$(4.22 \pm 0.07) \times 10^{-2}$	$(3.92 \pm 0.07) \times 10^{-2}$

V_{ub} $(3.81 \pm 0.40) \times 10^{-3}$

V_{cb} $(4.09 \pm 0.11) \times 10^{-2}$

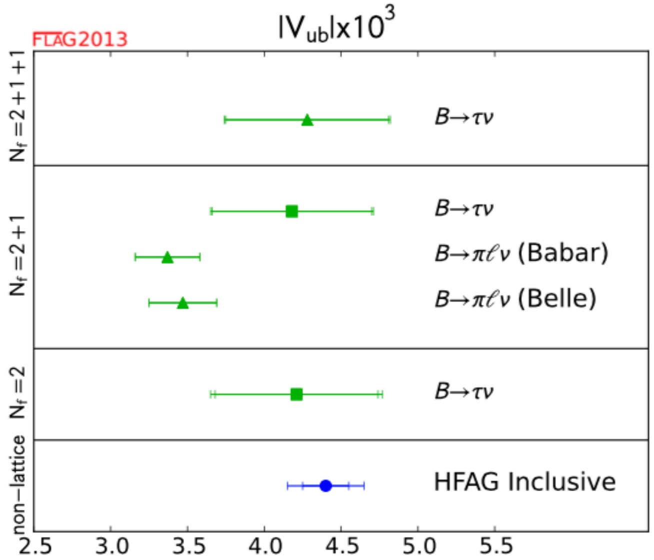
$\sin 2\beta_{exp} =$
0.680 ± 0.024

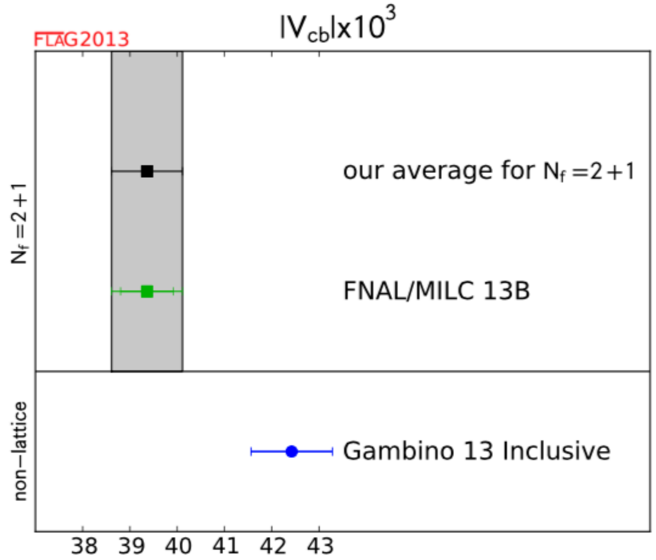
$\sin 2\beta_{UTfit} =$
0.747 ± 0.039
$B_K = 0.84 \pm 0.07$

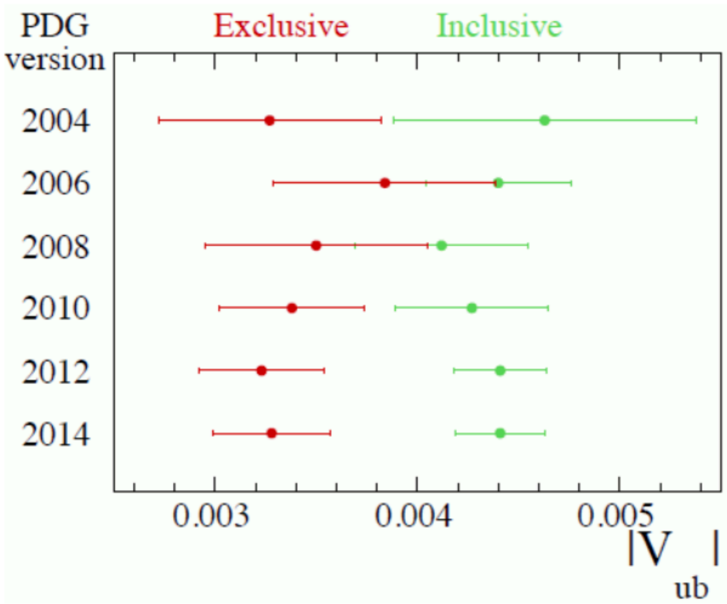
$\sin 2\beta_{incl} =$
0.782 ± 0.028
$B_K = 0.74 \pm 0.05$

$\sin 2\beta_{excl} =$
0.725 ± 0.019
$B_K = 0.93 \pm 0.07$

$|V_{ub}|$, $|V_{cb}|$







Courtesy of C. Pena
Lattice 2015

Courtesy of Denis Derkach

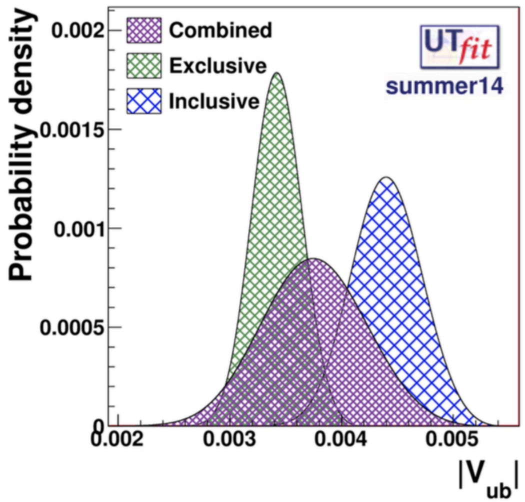
The relative ratio of CKM elements is easily calculable:

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1 - \frac{\lambda^2}{2}}\sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

QCD corrections to be considered

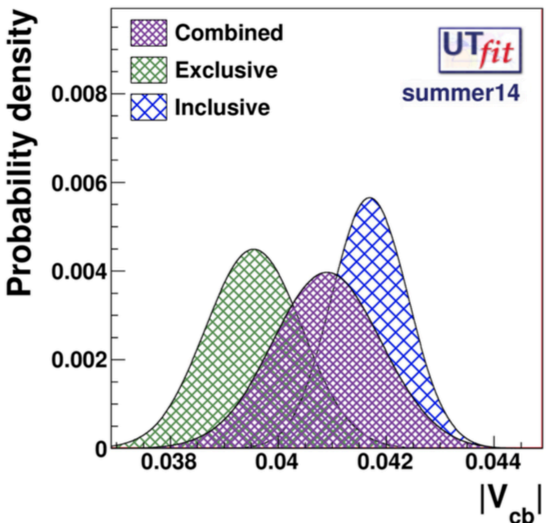
•inclusive measurements: OPE

•exclusive measurements: form-factors from lattice QCD



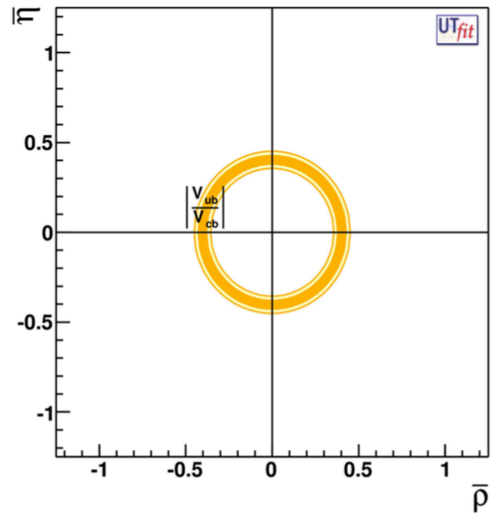
V_{ub}(excl) = (3.42 ± 0.22) 10^{-3}
V_{ub}(incl) = (4.40 ± 0.31) 10^{-3}
V_{ub} = (3.75 ± 0.46) 10^{-3}

~1.9 σ discrepancy

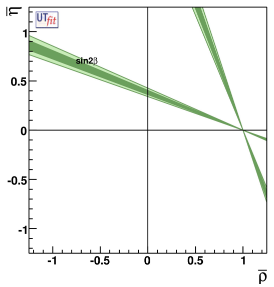


V_{cb}(excl) = (39.55 ± 0.88) 10^{-3}
V_{cb}(incl) = (41.7 ± 0.7) 10^{-3}
V_{cb} = (40.9 ± 1.0) 10^{-3}

~2.5 σ discrepancy



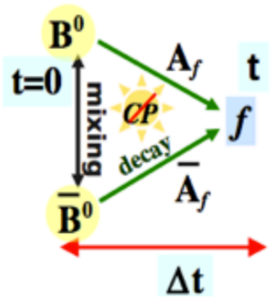
There is still an inconsistency between inclusive and exclusive measurements. We take this into account inflating the combined uncertainty (a-la PDG).



Beta results

$B^0 \to J/\Psi K^0$

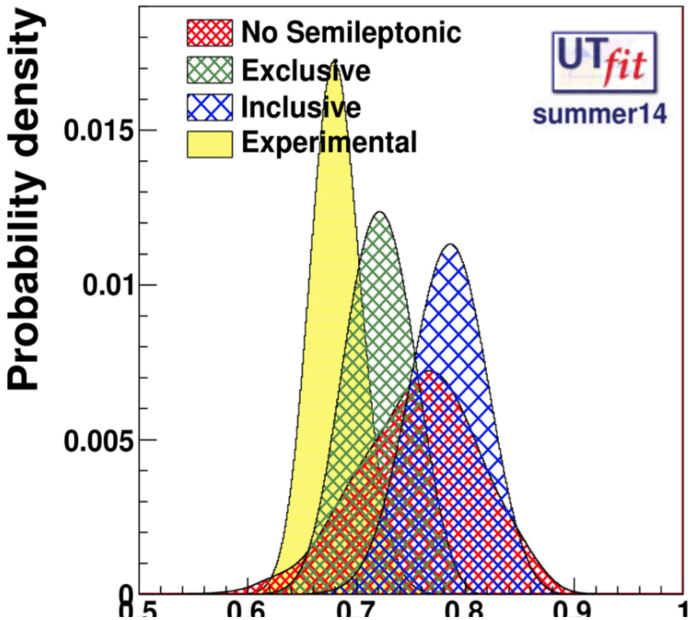
sin2β from time-dependent A_{CP} in $B \to J/\psi K$



$$a_{f_{CP}}(t) = \frac{\mathrm{Prob}(B^0(t) \to f_{CP}) - \mathrm{Prob}(\overline{B^0}(t) \to f_{CP})}{\mathrm{Prob}(\overline{B^0}(t) \to f_{CP}) + \mathrm{Prob}(B^0(t) \to f_{CP})} = C_f \cos \Delta m_d t \; + \; S_f \sin \Delta m_d t$$

The decay is dominated by a single (tree level) amplitude, thus a can be simplified:

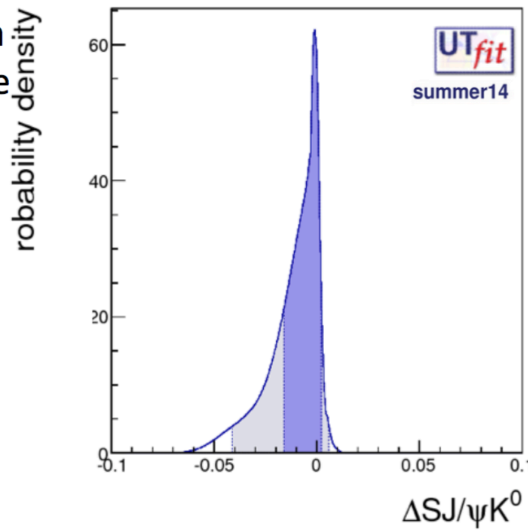
$$\boxed{a_{f_{CP}}(t) = -\eta_{CP} \sin(\Delta m_d t) \sin 2\beta}$$



We also analise $\bar{B}^0 \to J/\psi \pi^0$ to obtain the theoretical uncertainty related to the penguin polution in data-driven way. This gives us an additional correction:

data-driven theoretical uncertainty

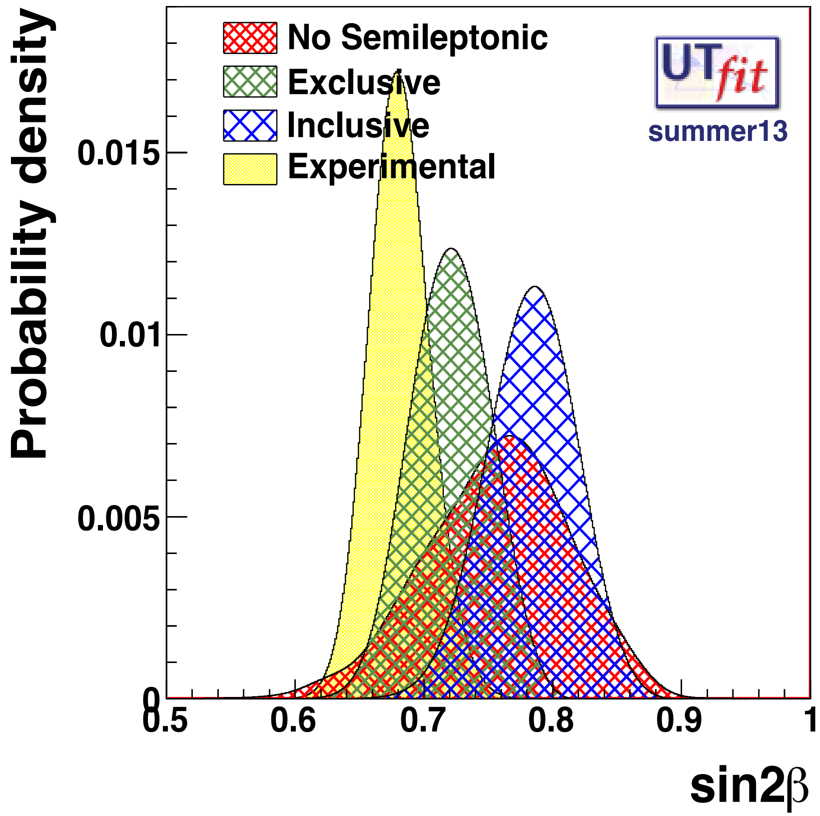
$\Delta S \in [-0.02, 0.00]$ at 68% prob.



$$\sin(2\beta) = (0.680 \pm 0.023)$$

inclusives vs exclusives

$\sin 2\beta_{exp}$ =
0.680 ± 0.024



only exclusive values

$\sin 2\beta_{UTfit}$ = 0.726 ± 0.020

~1.3σ

only inclusive values

$\sin 2\beta_{UTfit}$ = 0.781 ± 0.027

~2.6σ

$\sin 2\beta_{UTfit}$ = 0.709 ± 0.029

~0.9σ

preliminary

Many of the tensions of the past unfortunately disappeared

There still remain important differences between inclusive and exclusive determinations of V_{ub} and V_{cb}

But this seems rather to be a theory problem !!

Is the present picture showing a Model Standardissimo ?

An evidence, an evidence, my kingdom for an evidence

From Shakespeare's *Richard III*

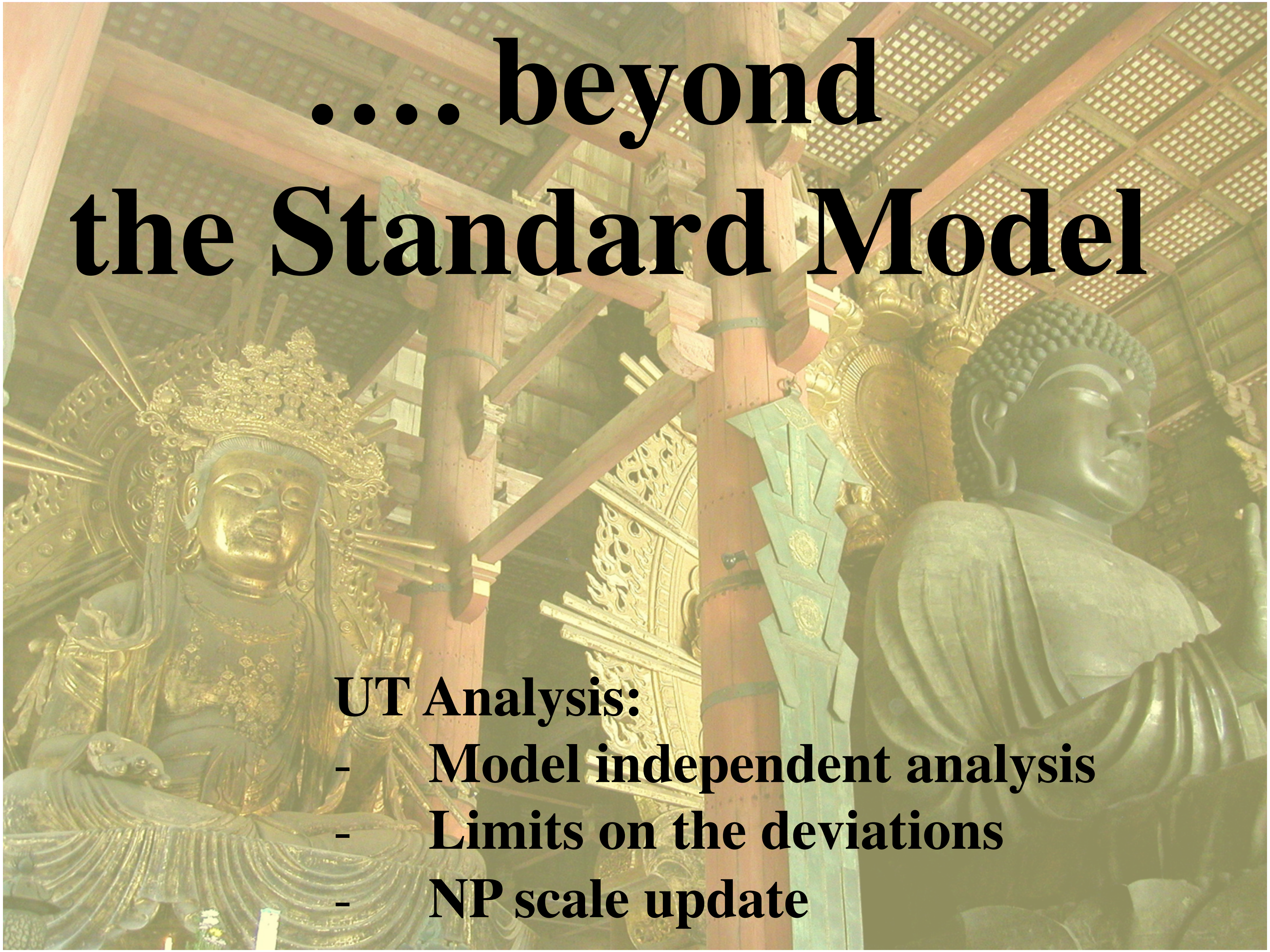
1) Fit of NP-ΔF=2 parameters in a Model "independent" way

2) "Scale" analysis in ΔF=2

What for a ``standardissimo" CKM which agrees so well with the experimental observations?

New Physics at the EW scale is "flavor blind" -> MINIMAL FLAVOR VIOLATION, namely flavour originates only from the Yukawa couplings of the SM

New Physics introduces new sources of flavor, the contribution of which, at most $<$ 20 % , should be found in the present data, e.g. in the asymmetries of Bs decays



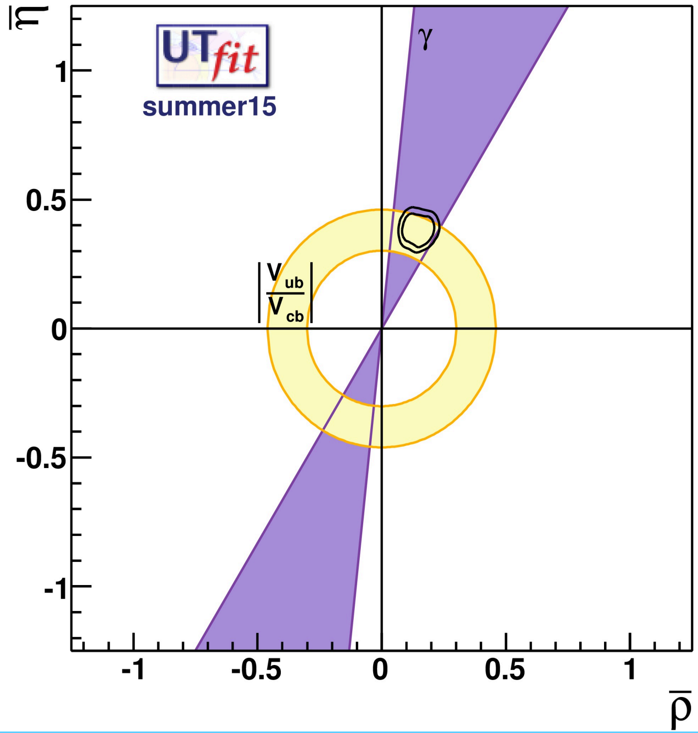
…. beyond the Standard Model

UT Analysis:

- Model independent analysis
- Limits on the deviations
- NP scale update

Only tree level processes Vub/Vcb and B-> DK$^{(*)}$

CP VIOLATION PROVEN IN THE SM !!



Three generations, no NP in tree level decays, no large NP EWP in B $\pi\pi$

degeneracy of γ broken by A_{SL}

$$\Delta m_s = |A_s| = C_{B_s} \Delta m_s^{SM}$$

$$2\phi_s = -arg A_s = 2\,(\beta_s - \phi_{B_s})$$

$$A_{SL}^s = \frac{\Gamma(\bar{B}_s \to l^+X) - \Gamma(B_s \to l^-X)}{\Gamma(\bar{B}_s \to l^+X) + \Gamma(B_s \to l^-X)} = Im\left(\frac{\Gamma_{12}^s}{A_s}\right)$$

Main Ingredients and General Parametrizations

Fit simultaneously CKM and NP parameters (generalized Utfit)

$$H^{\Delta F=2} = \hat{m} - \frac{i}{2}\hat{\Gamma} \quad A = \hat{m}_{12} = \langle \bar{M}|\hat{m}|M\rangle \quad \Gamma_{12} = \langle \bar{M}|\hat{\Gamma}|M\rangle$$

Neutral Kaon Mixing

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

B_d and B_s mixing

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

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{SM} e^{-2i\beta_s} + A_s^{NP} e^{2i(\phi_s^{NP}-\beta_s)}}{A_s^{SM} e^{-2i\beta_s}} = \frac{\langle \bar{B}_s | H_{eff}^{full} | B_s \rangle}{\langle \bar{B}_s | H_{eff}^{SM} | B_s \rangle}$$

$$\begin{aligned} \frac{\Gamma_{12}^q}{A_q} = -2\frac{\kappa}{C_{B_q}} \Bigg\{ & e^{i2\phi_{B_q}} \left(n_1 + \frac{n_6 B_2 + n_{11}}{B_1}\right) - \frac{e^{i(\phi_q^{SM}+2\phi_{B_q})}}{R_t^q} \left(n_2 + \frac{n_7 B_2 + n_{12}}{B_1}\right) \\ & + \frac{e^{i2(\phi_q^{SM}+\phi_{B_q})}}{R_t^{q^2}} \left(n_3 + \frac{n_8 B_2 + n_{13}}{B_1}\right) + e^{i(\phi_q^{Pen}+2\phi_{B_q})} C_q^{Pen} \left(n_4 + n_9 \frac{B_2}{B_1}\right) \\ & - e^{i(\phi_q^{SM}+\phi_q^{Pen}+2\phi_{B_q})} \frac{C_q^{Pen}}{R_t^q} \left(n_5 + n_{10} \frac{B_2}{B_1}\right) \Bigg\} \end{aligned}$$

C_q^{Pen} and ϕ_q^{Pen} parametrize possible NP contributions to Γ^q_{12} from b -> s penguins

Physical observables

$$\Delta m_s = |A_s| = C_{B_s} \Delta m_s^{SM}$$

$$2\phi_s = -arg\, A_s = 2\left(\beta_s - \phi_{B_s}\right)$$

$$A_{SL}^s = \frac{\Gamma(\bar{B}_s \to l^+ X) - \Gamma(B_s \to l^- X)}{\Gamma(\bar{B}_s \to l^+ X) + \Gamma(B_s \to l^- X)} = Im\left(\frac{\Gamma_{12}^s}{A_s}\right)$$

$$A_{SL}^{\mu\mu} = \frac{f_d \chi_{d0} A_{SL}^d + f_s \chi_{s0} A_{SL}^s}{f_d \chi_{d0} + f_s \chi_{s0}}$$

$$\frac{\Delta\Gamma_s}{\Delta m_s} = Re\left(\frac{\Gamma_{12}^s}{A_s}\right) \qquad \tau_{B_s}^{FS} = \frac{1}{\Gamma_S} \frac{1 + (\Delta\Gamma_s/2\Gamma_s)^2}{1 - (\Delta\Gamma_s/2\Gamma_s)^2}$$

NP model independent Fit $\Delta F=2$

Parametrizing NP physics in $\Delta F=2$ processes

$$\boxed{C_{B_q} e^{2i\phi_{B_q}} = \frac{A^{NP}_{\Delta B=2} + A^{SM}_{\Delta B=2}}{A^{SM}_{\Delta B=2}}}$$

$$\Delta m_d^{EXP} = C_{B_d} \Delta m_d^{SM} \qquad f(\rho,\eta,C_{B_d},QCD..)$$

$$A_{CP}(J/\Psi,K^0) = \sin(2\beta + 2\phi_{B_d}) \qquad f(\rho,\eta,\phi_{B_d})$$

$$\alpha^{EXP} = \alpha^{SM} - \phi_{B_d} \qquad f(\rho,\eta,\phi_{B_d})$$

$$|\varepsilon_K|^{EXP} = C_\varepsilon |\varepsilon_K|^{SM} \qquad f(\rho,\eta,C_\varepsilon,QCD..)$$

$$\Delta m_s^{EXP} = C_{B_s} \Delta m_s^{SM} \qquad f(\rho,\eta,C_{Bs},QCD..)$$

$$A_{CP}(J/\Psi,\phi) = \sin(2\beta_s - 2\phi_{B_s}) \qquad f(\rho,\eta,\phi_{B_s})$$

...

		ρ,η	C_d	φ_d	C_s	φ_s	$C_{\varepsilon K}$
Tree processes	γ (DK)	X					
	V_{ub}/V_{cb}	X					
$1\leftrightarrow3$ family	Δm_d	X	X				
	ACP (J/Ψ K)	X		X			
	ACP ($D\pi(\rho)$,$DK\pi$)	X		X			
	A_{SL}		X	X			
	α ($\rho\rho,\rho\pi,\pi\pi$)	X		X			
	A_{CH}		X	X	X	X	
$2\leftrightarrow3$ family	$\tau(Bs)$, $\Delta\Gamma_s/\Gamma_s$				X	X	
	Δm_s				X		
	ASL(Bs)				X	X	
	ACP (J/Ψ ϕ)	~X				X	
$1\leftrightarrow2$ familiy	ε_K	X					X

5 new free parameters

C_s, φ_s B_s mixing

C_d, φ_d B_d mixing

$C_{\varepsilon K}$ K mixing

Today :

fit is overcontrained

Possible to fit 7 free parameters

(ρ, η, C_d, φ_d, C_s, φ_s, $C_{\varepsilon K}$)

SM analysis → **NP-ΔF=2 analysis**

$\rho = 0.142 \pm 0.019$ → $\rho = 0.147 \pm 0.043$

$\eta = 0.348 \pm 0.013$ → $\eta = 0.384 \pm 0.044$

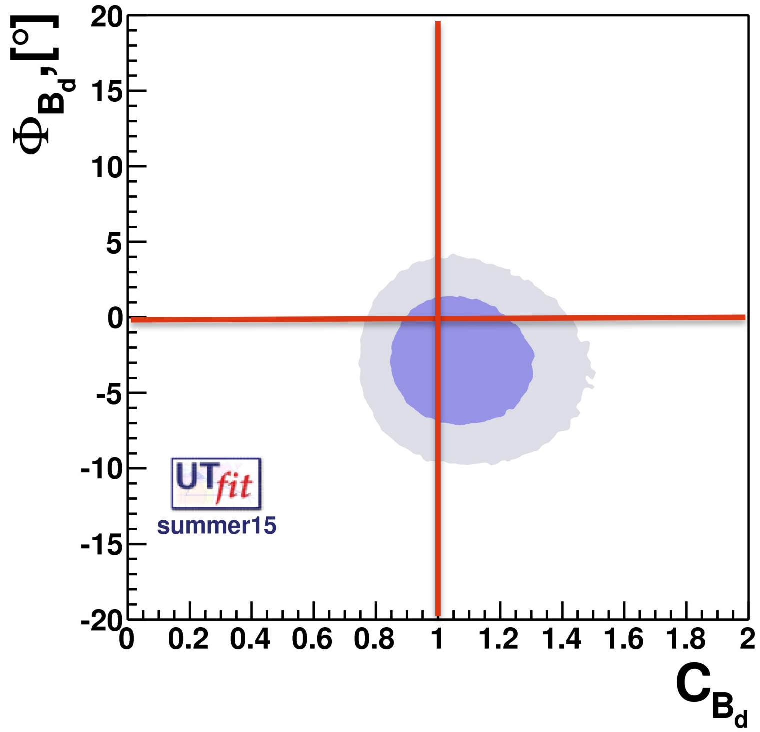
ρ,η fit quite precisely in NP-ΔF=2 analysis and consistent with the one obtained on the SM analysis

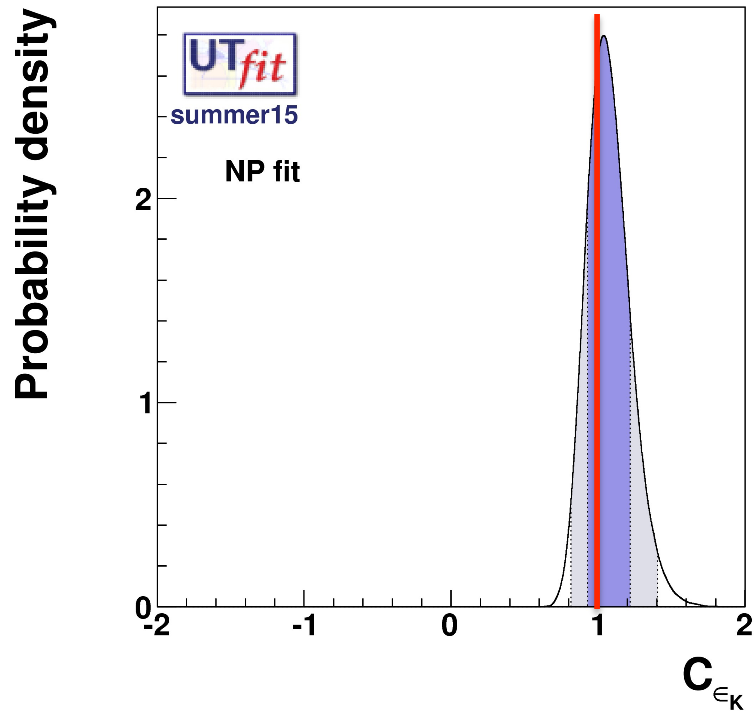
[error double]

(main contributors tree-level γ and V_{ub})

Please consider these numbers when you want to get CKM parameters in presence of NP in ΔF=2 amplitudes (all sectors 1-2,1-3,2-3)

NP parameters (i)





$$C_{B_d} = 1.09 \pm 0.15$$

$$\phi_{B_d} = (-2.9 \pm 2.8)^0$$

$$C_{\varepsilon_K} = 1.07 \pm 0.14$$

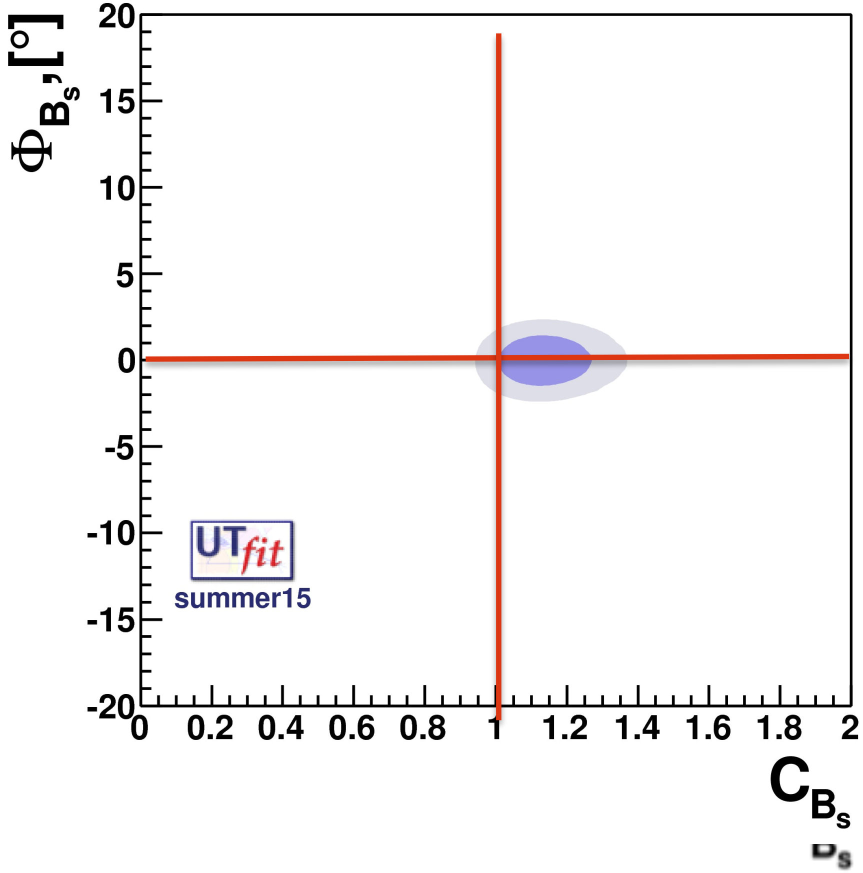
$$\Delta m_d = C_{B_d} (\Delta m_d)^{SM} \qquad a_{CP}^{B_d \to J/\psi K_S} \to \sin 2(\beta + \varphi_{B_d})$$

$$a_{SL}^d = \mathrm{Im}\left(\Gamma_{12}^d / A_d\right) \qquad \Delta\Gamma^d / \Delta m_d = \mathrm{Re}\left(\Gamma_{12}^d / A_d\right)$$

$$\mathrm{Im}\, A_K = C_\varepsilon\, \mathrm{Im}\, A_K^{SM}$$

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

NP parameters (ii)



C_{B_s}= 1.14 ± 0.09

Φ_{Bs}= $(-0.1 \pm 1.0)^0$

$$\Delta m_s = C_{B_s} (\Delta m_s)^{SM} \qquad a_{CP}^{B_s \to J/\psi\varphi} \to -\beta_s + \varphi_{B_s}$$

$$a_{SL}^s = \mathrm{Im}\left(\Gamma_{12}^s / A_s\right) \qquad \Delta\Gamma^s / \Delta m_s = \mathrm{Re}\left(\Gamma_{12}^s / A_s\right)$$

TESTING THE NEW PHYSICS SCALE

Effective Theory Analysis ΔF=2

$$C_j(\Lambda) = \frac{LF_j}{\Lambda^2} \Rightarrow \Lambda = \sqrt{\frac{LF_j}{C_j(\Lambda)}}$$

Effective Hamiltonian in the mixing amplitudes

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

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

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

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

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

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

C(Λ) coefficients are extracted from data

L is loop factor and should be :
L=1 tree/strong int. NP
L=α_s^2 or α_W^2 for strong/weak perturb. NP

$F_1 = F_{SM} = (V_{tq} V_{tb}^*)^2$ $F_{j=1} = 0$	**MFV**
$\lvert F_j \rvert = F_{SM}$ arbitrary phases	**NMFV**
$\lvert F_j \rvert = 1$ arbitrary phases	**Flavour generic**

Results from a fit to the Wilson Coefficients

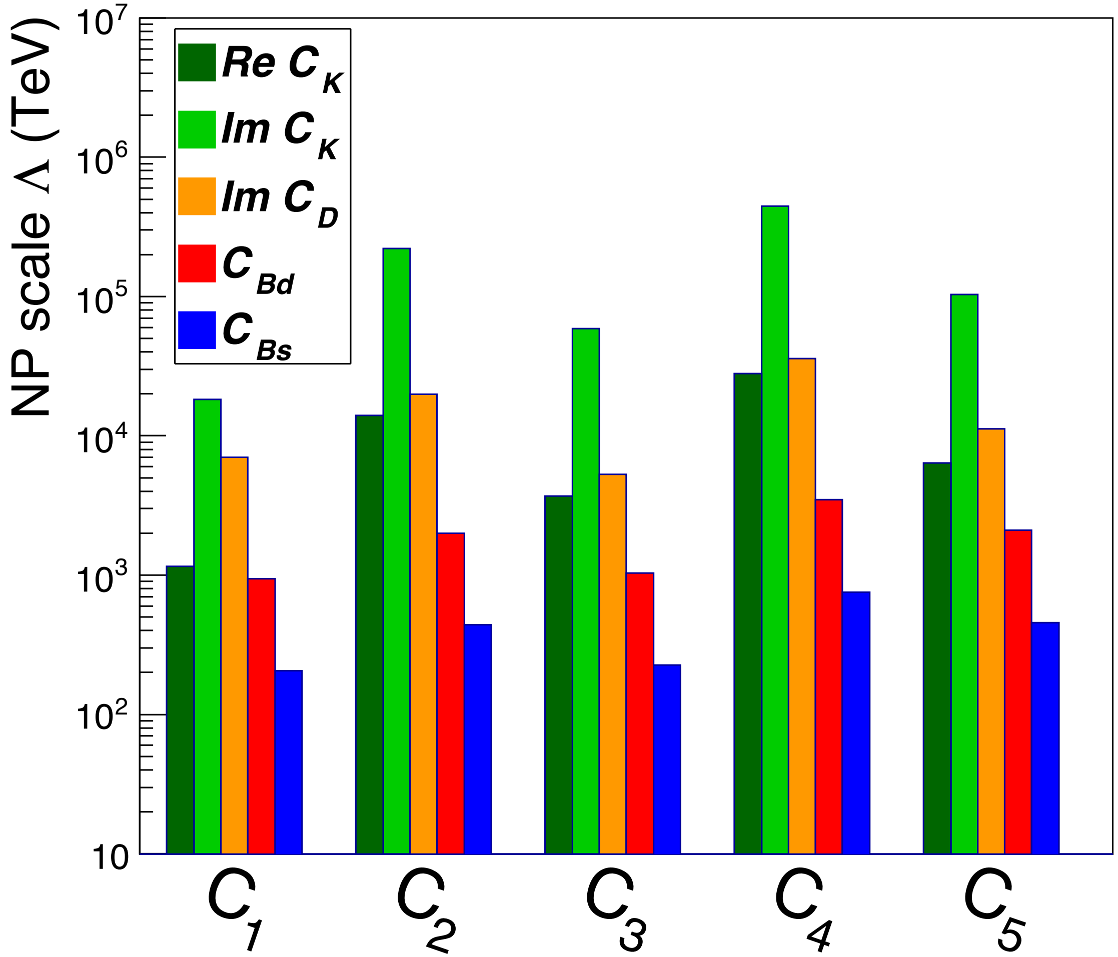
Results obtained with L=1 corresponding to tree level NP effects and an arbitrary flavor structure

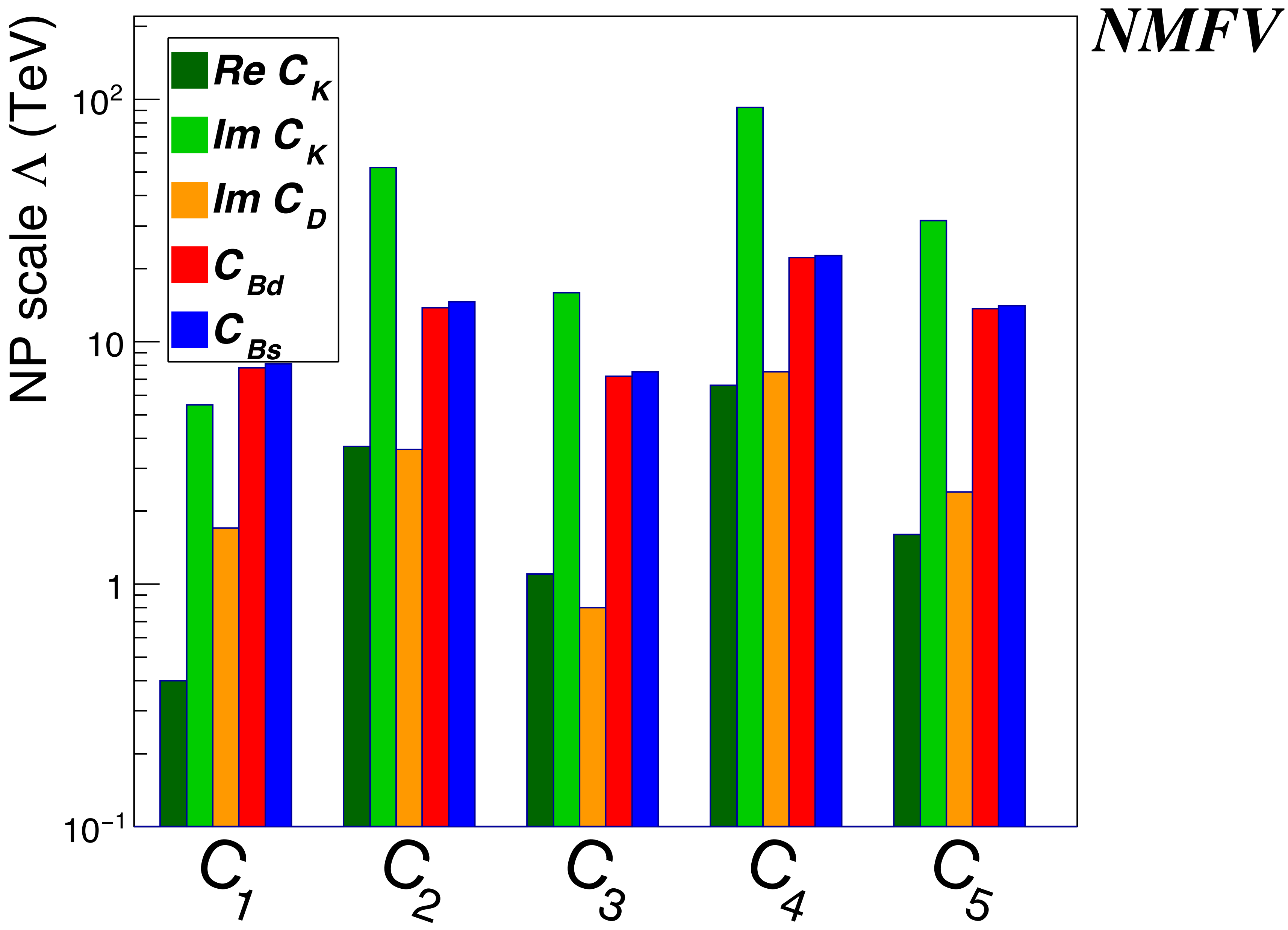
$\varepsilon_K \quad \Lambda = 5\ 10^5$ TeV

$D \quad \Lambda = 10^4$ TeV

$B_d \quad \Lambda = 3\ 10^3$ TeV

$B_s \quad \Lambda = 8\ 10^2$ TeV





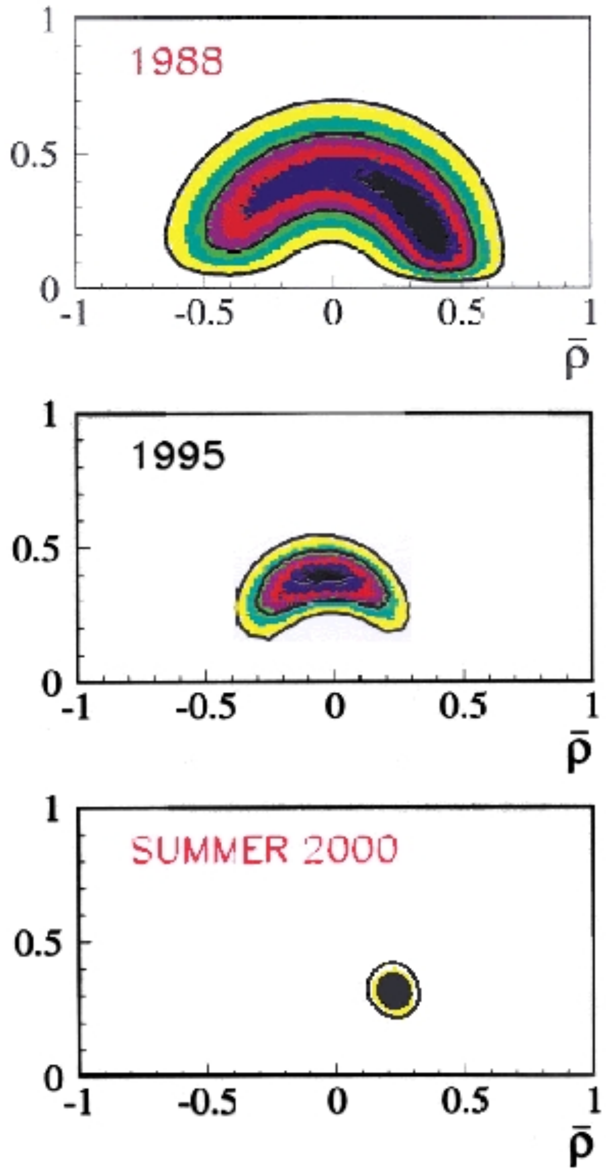
NMFV
NP scale Λ (TeV)
Re C_K
Im C_K
Im C_D
C_Bd
C_Bs
10^2
10
1
10^-1
C_1
C_2
C_3
C_4
C_5

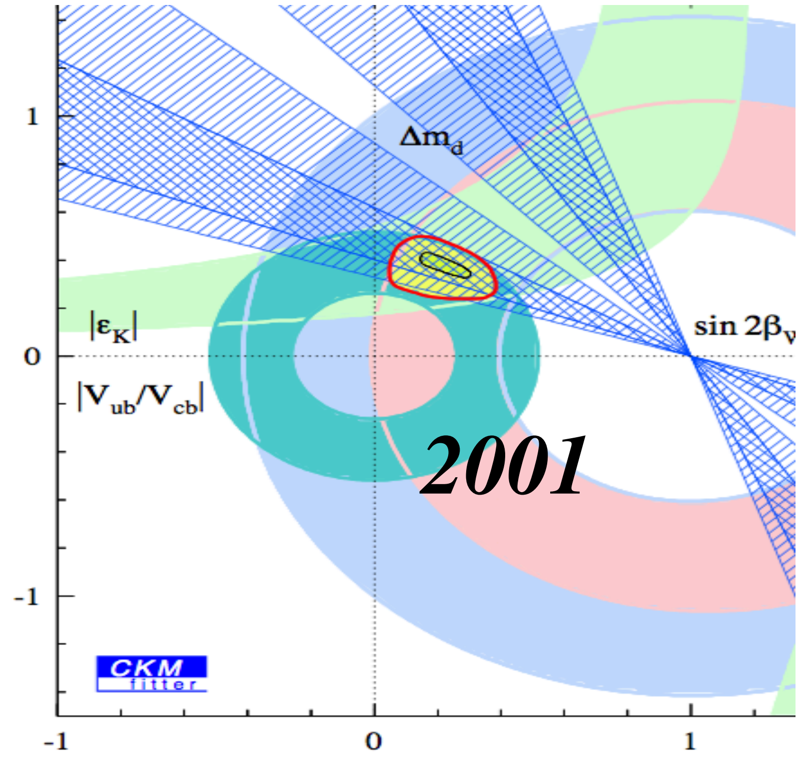
CONCLUSIONS

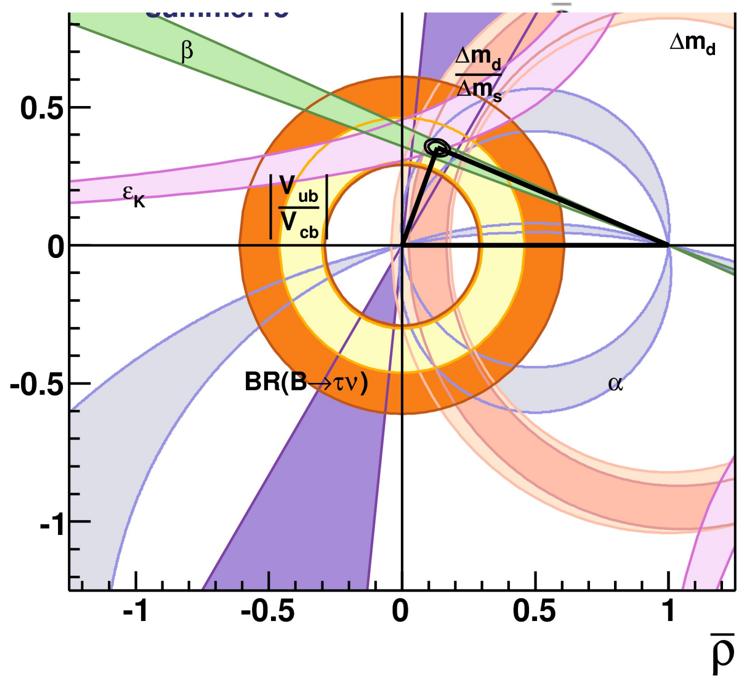
1) The high precision of the SM UT Analysis allows to test the SM and to search for NP at a level which is competitive with direct searches
2) CKM matrix is the dominant source of flavour mixing and CP violation $\sigma(\rho)$~15% & $\sigma(\eta)$ ~4%. SM analysis shows a very good overall consistency
3) The main tensions disappeared
4) Inclusive vs exclusive semileptonic decays still need theoretical improvement and BK !!

Thus for the time being we have to remain with a STANDARDISSIMO STANDARD MODEL but …

CONCLUSIONS: THANKS TO EXPERIMENTAL MEASUREMENTS & IMPROVED LATTICE CALCULATIONS







THANKS FOR YOUR ATTENTION

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