MATTER-ANTIMATTER ASYMMETRY In the Standard Model and Beyond

AST Ateneo della Scienza e della Tecnologia

UTfit

DIPARTIMENTO DI FISICA

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI ROMA LA SAPIENZA

Trieste 3 Febbraio 2010

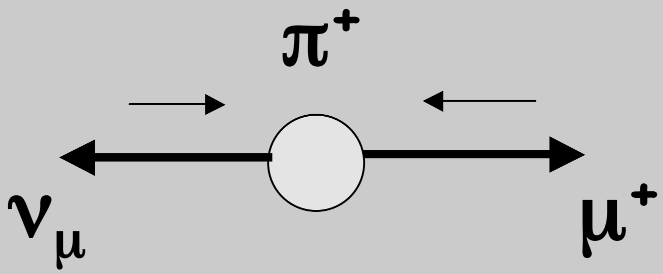
Guido Martinelli

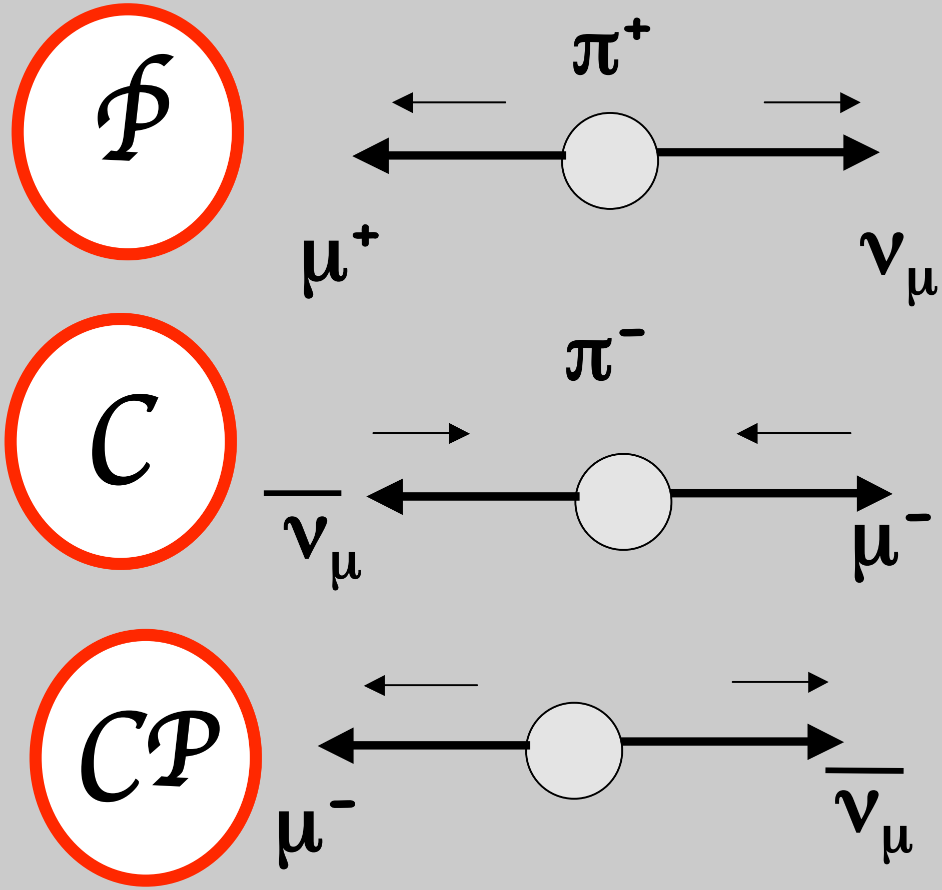
Matter ⇔ Antimatter Asymmetry

In the Standard Model and Beyond

- Antimatter in the Univers and ~~CP~~
- ~~CP~~, masses and weak couplings
- ~~CP~~ for Kaon and B mesons in the SM and beyond
- Conclusions and outlook

Relativistic Quantum Mechanics → Antimatter CPT Theorem





CP Violation was discovered about 37 years ago in K^0 - $\overline{K^0}$ mixing

(weak interactions)

If not for C (Charge conjugation) and CP (C & Parity) violation fundamental phenomena would be the same for matter & antimatter, thus **<u>we should have a universe filled with antimatter</u>**

Since antimatter annihilates matter producing an enormous quantity of energy, for example high energy photons, <u>a diffused and massive presence of antimatter would have been already detected</u>

instead

ALL ANTIMATTER PRODUCED IN OUR LABORATORIES DOES NOT EXCEED 10^{-12} GRAMS !!!

P.A.M. Dirac

C.D. Anderson 1932

The second step of Amstrong on the moon shows that antimatter is negligible on planetary scales

ANTIMATTER FROM COSMIC RAYS IS ABOUT $1/10^5$ OF MATTER

THE ABSENCE OF VISIBLE EXPLOSIONS
IN THE UNIVERSE
EXCLUDES THE PRESENCE OF
ANTIMATTER
UP TO DISTANCES OF
O(20 MEGAPARSECS)
(ONE PARSEC ~ 3.26 LIGHT YEARS
~ 3.1 10^{18} cm)

$$\beta = \frac{N_B - N_{\bar{B}}}{N_\gamma} = 6 \times 10^{-10}$$

$$N_\gamma = 412 \ /cm^3$$


WHEN AND WHY
ANTIMATTER DISAPPEARED ?

In 1967 Andrei Sakharov pointed out that, for the universe to evolve from the initial matter-antimatter fireball to the present matter antimatter asymmetric state, 4 conditions must be fulfilled:

1) Baryon number violation $\Delta B \neq 0$ (GUT ??)

$$e^+ + \bar{d} \rightarrow X \rightarrow u + u \qquad (\Delta(B-L) = 0)$$

Lepton number violation is possible but not necessary and could be zero because of the presence of a large number of antineutrinos

2) Charge symmetry violation $\not{C}$

$$\Gamma(e^+ + \bar{d} \rightarrow X \rightarrow u + u) \neq \Gamma(e^- + d \rightarrow X \rightarrow \bar{u} + \bar{u})$$

3) $\not{CP}$ violation: the number of left handed up quarks produced by X must be different from the number of right handed up antiquarks

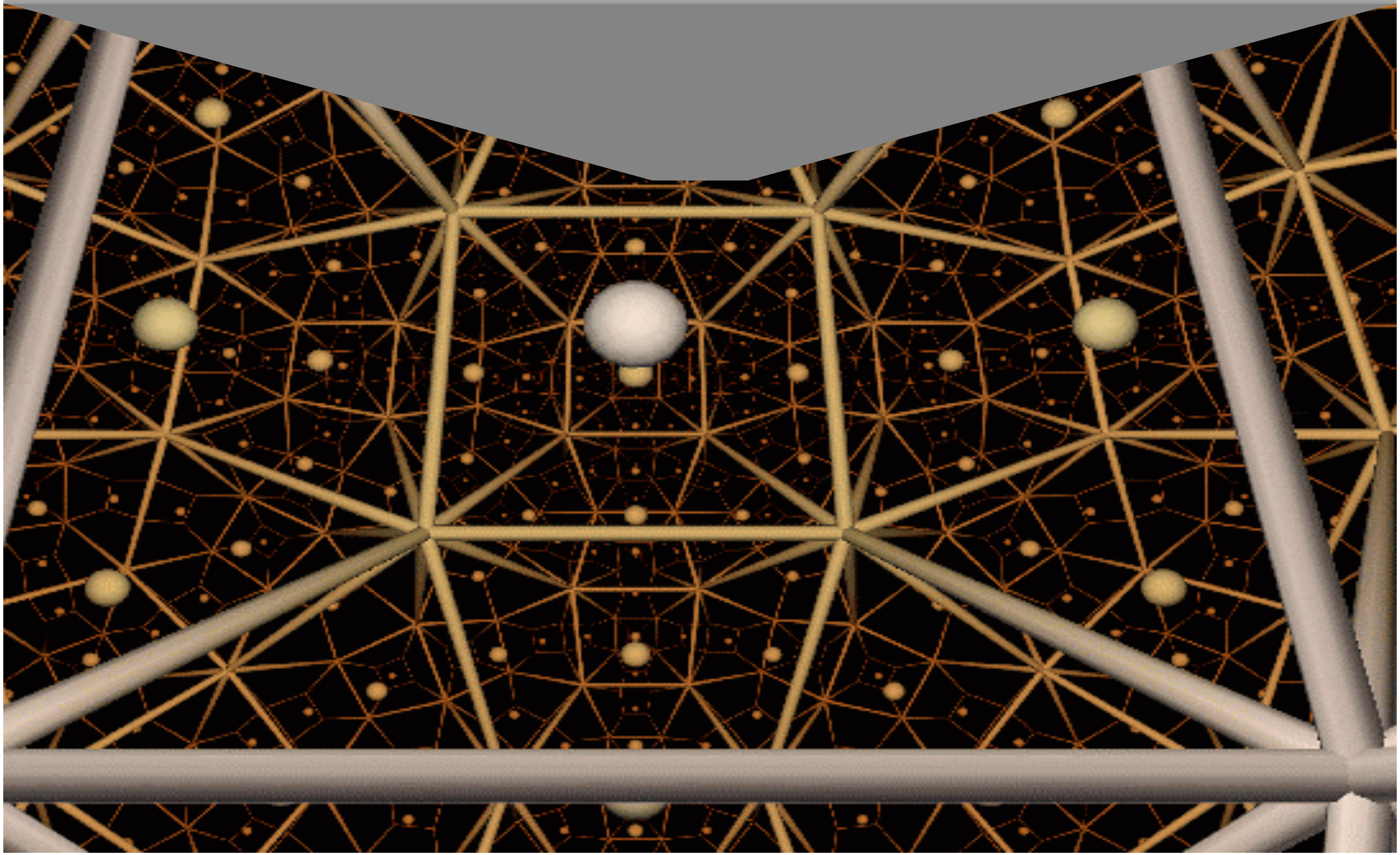
4) The universe was not in equilibrium when this happened, otherwise if

$$\Gamma(e^+ + \bar{d} \rightarrow u + u) > \Gamma(e^- + d \rightarrow \bar{u} + \bar{u})$$

then also

$$\Gamma(u + u \rightarrow e^+ + \bar{d}) > \Gamma(\bar{u} + \bar{u} \rightarrow e^- + d)$$

The amount of $\not{CP}$, discovered in 1964 in mixing (see below) is however too small to explain the scarcity of antimatter in the universe.



CP Violation in the Standard Model

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

Mass terms are forbidden by simmetries :

$$q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_R\ d_R$$

$$m\,\bar{q}q = m\,(\bar{q}_L q_R + \bar{q}_R q_L)$$

Hermiticity guaranties CP conservation for $\mathcal{L}^{weak\ int}$:

$$\mathcal{L}_{CC}^{weak\ int} = \frac{g_W}{\sqrt{2}}\,(J^-_\mu W^+_\mu + J^+_\mu W^-_\mu)$$

$$J^+_\mu = \bar{u}\,\gamma_\mu\,(1 - \gamma_5)\,d + \ldots$$

$(u \to c, d \to s) + (u \to t, d \to b)$

$\mathcal{P}$ $\quad \bar{u}\,\gamma_\mu\,d \to \bar{u}\,\gamma^\mu\,d$

$\quad \bar{u}\,\gamma_\mu\,\gamma_5\,d \to -\,\bar{u}\,\gamma^\mu\,\gamma_5\,d$

$\mathcal{C}$ $\quad \bar{u}\,\gamma_\mu\,d \to -\,\bar{d}\,\gamma_\mu\,u \qquad \bar{u}\,\gamma_\mu\,\gamma_5\,d \to \bar{d}\,\gamma_\mu\,\gamma_5\,u$

In the Standard Model the quark mass matrix, from which the CKM Matrix and $\not{CP}$ 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

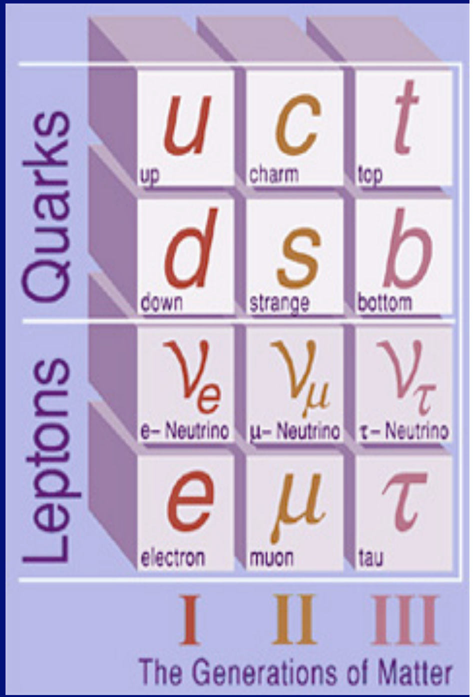
$\not{CP}$ and symmetry breaking are closely related !

QUARK FAMILIES

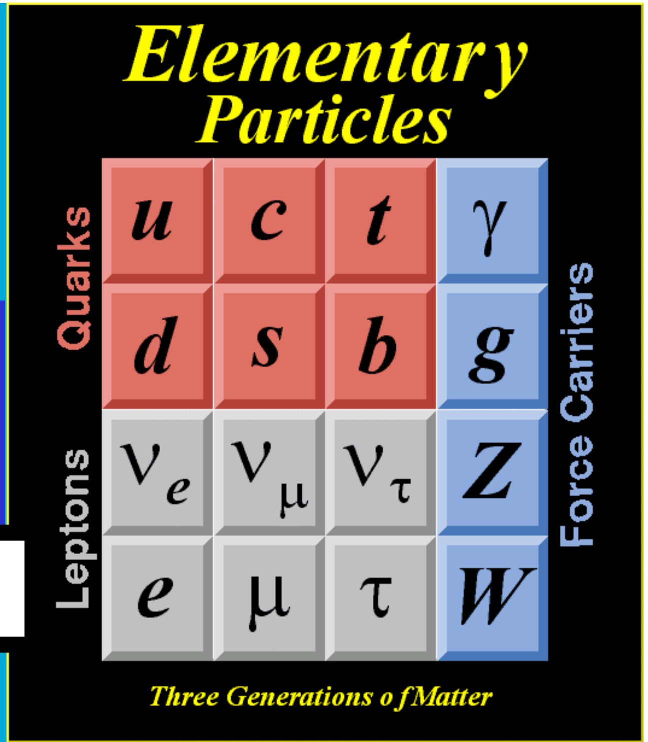
1) $q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ $U_R = u_R$, $D_R = d_R$

2) $q_L \equiv \begin{pmatrix} c_L \\ s_L \end{pmatrix}$ $U_R = c_R$, $D_R = s_R$

3) $q_L \equiv \begin{pmatrix} t_L \\ b_L \end{pmatrix}$ $U_R = t_R$, $D_R = b_R$



QUARK MASSES ARE GENERATED BY DYNAMICAL SYMMETRY BREAKING



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

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

Charge +2/3

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

Charge -1/3

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

$$\Sigma_{i,k=1,N} [\ m^{u}_{i,k} (\overline{u}^{i}_{L}\, u^{k}_{R}) + m^{d}_{i,k} (\overline{d}^{i}_{L}\, d^{k}_{R}) + h.c.\ ]$$

It is easy to show the a necessary and sufficient condition for CP invariance is

$$m^{u,d}_{i,k} = \text{real}$$

1) there is no compelling symmetry for $m^{u,d}_{i,k}$ to be real
2) in field theory, all that may happen will happen [see below]
3) symmetries and accidental symmetries
e.g. separate conservation of lepton and baryon numbers (it follows from gauge symmetry and renormalizability)

Diagonalization of the Mass Matrix

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

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

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

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

$$L^{weak\,int}_{CC} = \frac{g_W}{\sqrt{2}} \left(J^-_\mu W^+_\mu + h.c.\right)$$

$$\rightarrow \quad \frac{g_W}{\sqrt{2}} \left(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W^+_\mu + \ldots\right)$$

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. CP violation;

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)

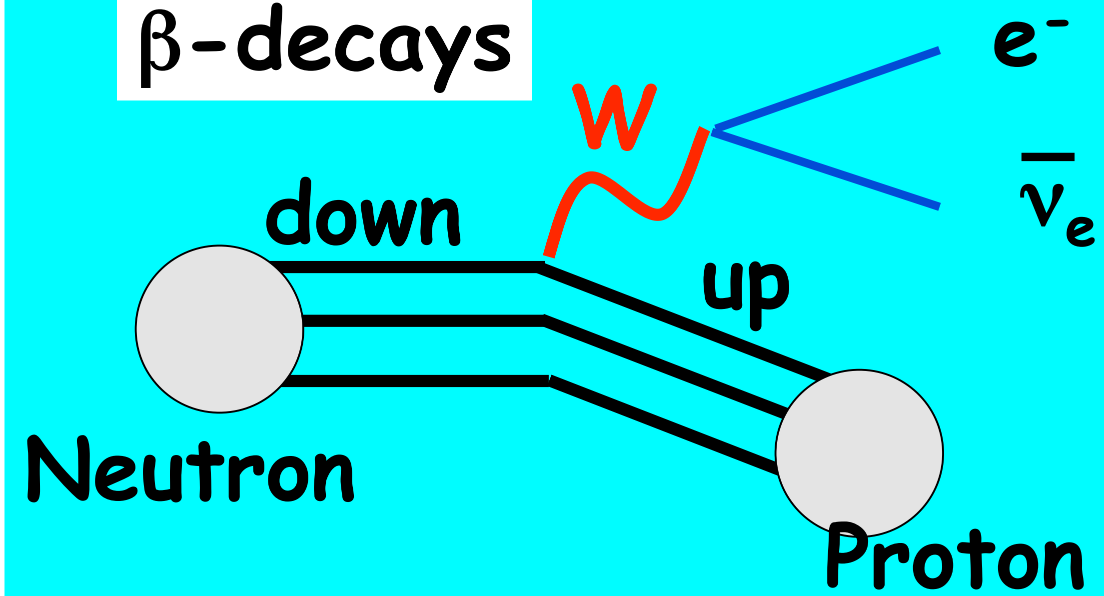
CP Violation is natural with three quark generations (Kobayashi-Maskawa)

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



$|V_{ud}| = 0.9735(8)$

$|V_{us}| = 0.2196(23)$

$|V_{cd}| = 0.224(16)$

$|V_{cs}| = 0.970(9)(70)$

$|V_{cb}| = 0.0406(8)$

$|V_{ub}| = 0.00409(25)$

$|V_{tb}| = 0.99(29)$

(0.999)

$$\frac{d\Gamma}{dq^2} \propto |V_{ij}|^2 f(q^2)^2$$

$c_{12}\ c_{13}$	$s_{12}\ c_{13}$	$s_{13}\ e^{-i\delta}$
$-s_{12}c_{23}$ $-c_{12}s_{23}s_{13}\ e^{i\delta}$	$c_{12}c_{23}$ $-s_{12}s_{23}s_{13}\ e^{i\delta}$	$s_{23}\ c_{13}$
$s_{12}s_{23}$ $-c_{12}c_{23}s_{13}\ e^{i\delta}$	$-c_{12}s_{23}$ $-s_{12}c_{23}s_{13}\ e^{i\delta}$	$c_{23}\ c_{13}$

$c_{ij} = \text{Cos}\ \theta_{ij}$ $s_{ij} = \text{Sin}\ \theta_{ij}$ $c_{ij} \geq 0$ $s_{ij} \geq 0$

$0 \leq \delta \leq 2\pi$ $|s_{12}| \sim \text{Sin}\ \theta_c$

for small angles $|s_{ij}| \sim |V_{ij}|$

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

$+ O(\lambda^4)$

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

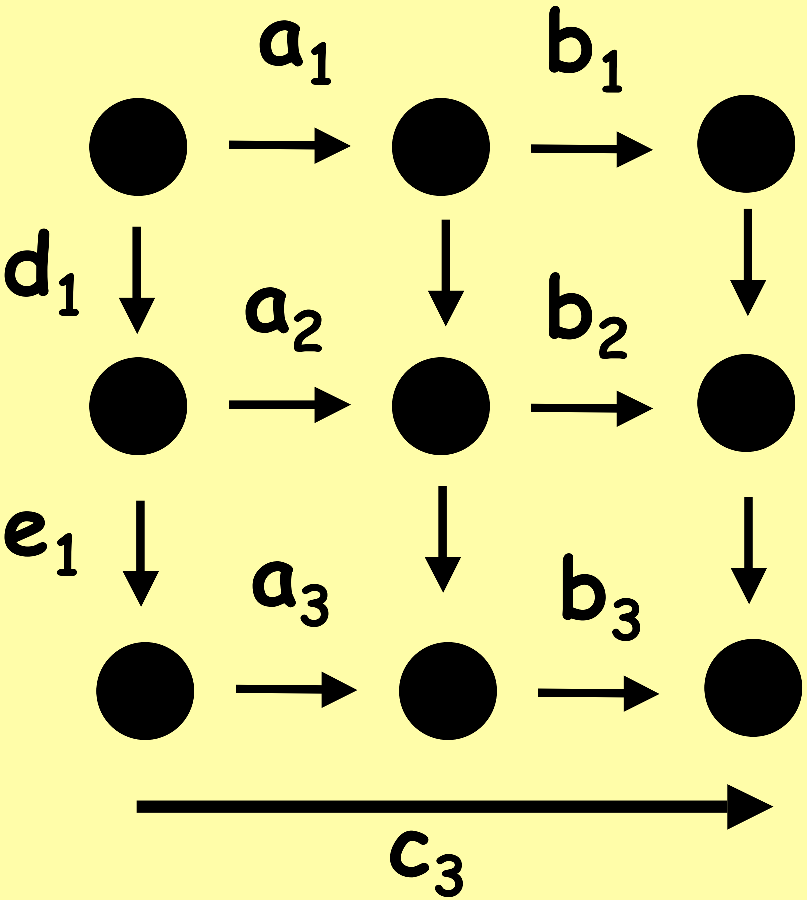
$\eta \sim 0.2$ $\rho \sim 0.3$

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

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

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

The Bjorken-Jarlskog Unitarity Triangle



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

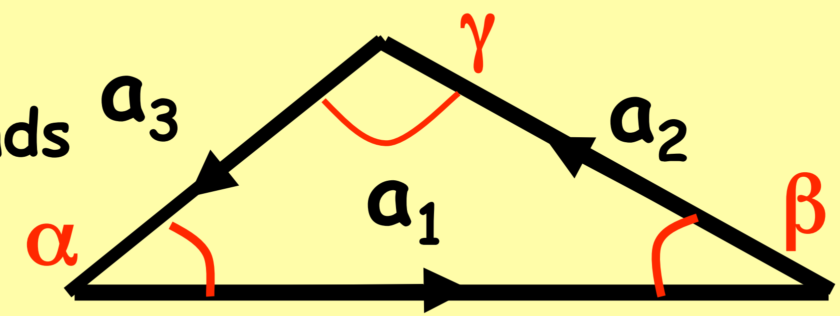
$a_1 = V_{11} V_{12}^* = V_{ud} V_{us}^*$

$a_2 = V_{21} V_{22}^* \quad a_3 = V_{31} V_{32}^*$

$a_1 + a_2 + a_3 = 0$

$(b_1 + b_2 + b_3 = 0$ etc.$)$

Only the orientation depends on the phase convention



Gluons and quarks

The QCD Lagrangian :

$$\mathcal{L}_{STRONG} = -1/4 \; G^{A}_{\mu\nu} G_{A}^{\mu\nu}$$

GLUONS

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

QUARKS (& **GLUONS**)

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

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

STRONG CP VIOLATION

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

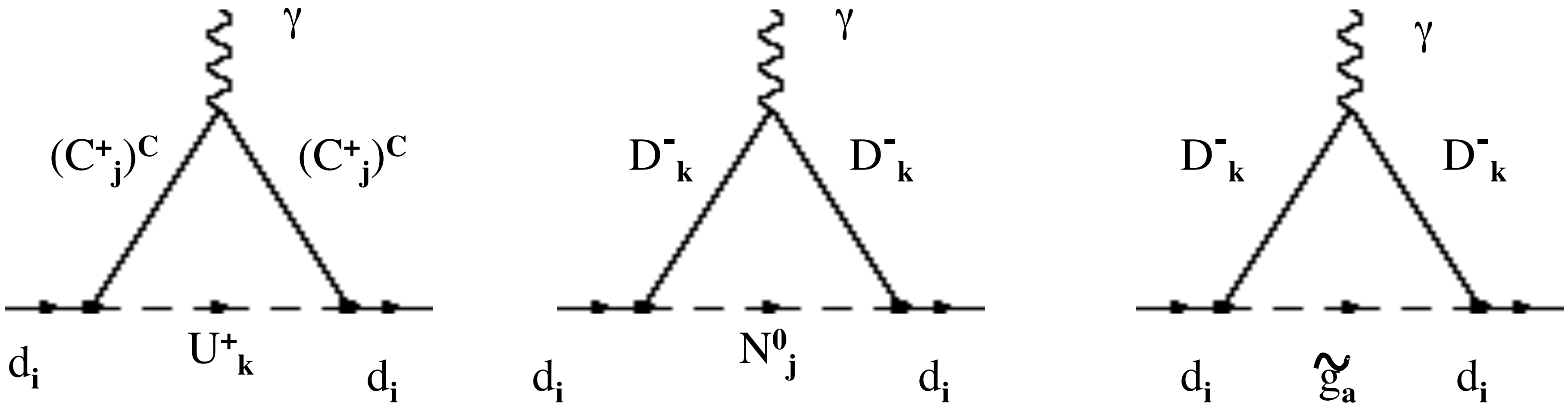
$$\mathcal{L}_\theta \sim \theta \, \vec{E}^a \cdot \vec{B}^a$$

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

$$e_n < 6.3 \, 10^{-26} \text{ e cm}$$

$\theta < 10^{-9}$ which is quite unnatural !!

Neutron electric dipole moment in SuperSymmetry



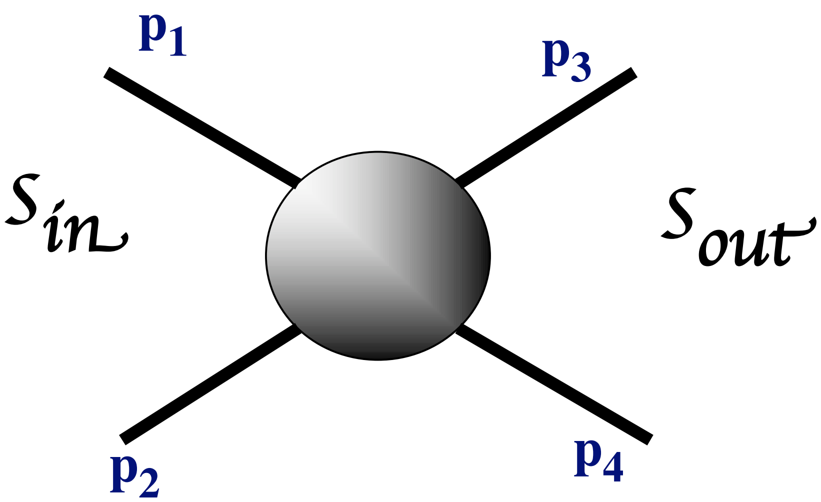
$C_{e,C,g}$ can be computed perturbatively

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

Consequences of a Symmetry

$$[\mathcal{S}, \mathcal{H}] = 0 \quad \rightarrow \quad | E, \mathbf{p}, \mathbf{s} \rangle$$

We may find states which are simultaneously eigenstates of $\mathcal{S}$ and of the Energy



$$CP\,|K_1^0\rangle = +\,|K_1^0\rangle$$

$$CP\,|K_2^0\rangle = -\,|K_2^0\rangle$$

$$\langle \pi\pi | K_1^0 \rangle \neq 0$$

$$\langle \pi\pi | K_2^0 \rangle = 0$$

$$|K_{S,L}^0\rangle = \alpha\,|K_1^0\rangle + \beta\,|K_2^0\rangle$$

if CP is conserved either α=0 or β=0

$\not{C}\not{P}$ Violation in the Neutral Kaon System

Expanding in several "small" quantities

$$\eta^{00} = \frac{\langle \pi^0\pi^0 | \mathcal{H}_W | K_L \rangle}{\langle \pi^0\pi^0 | \mathcal{H}_W | K_S \rangle} \sim \varepsilon - 2\,\varepsilon'$$

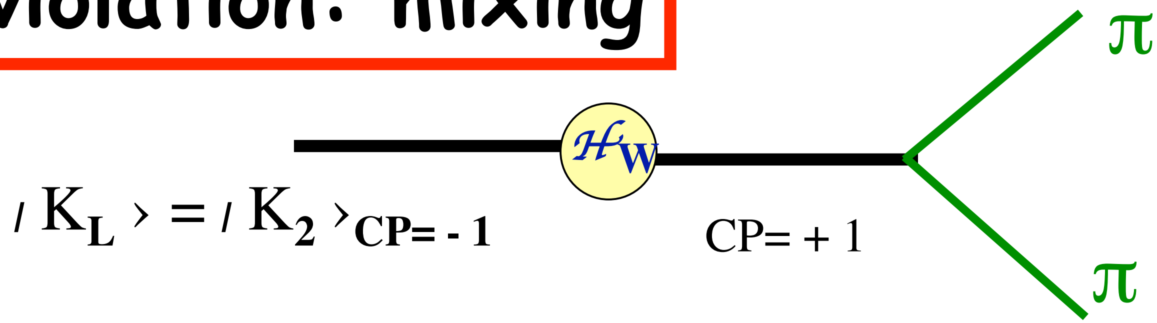
$$\eta^{+-} = \frac{\langle \pi^+\pi^- | \mathcal{H}_W | K_L \rangle}{\langle \pi^+\pi^- | \mathcal{H}_W | K_S \rangle} \sim \varepsilon + \varepsilon'$$

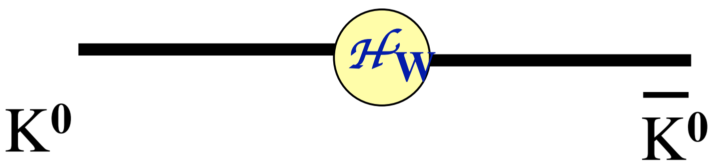
Conventionally:

$$| K_S \rangle = | K_1 \rangle_{CP=+1} + \varepsilon\, | K_2 \rangle_{CP=-1}$$

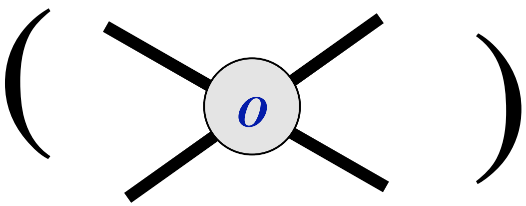
$$| K_L \rangle = | K_2 \rangle_{CP=-1} + \varepsilon\, | K_1 \rangle_{CP=+1}$$

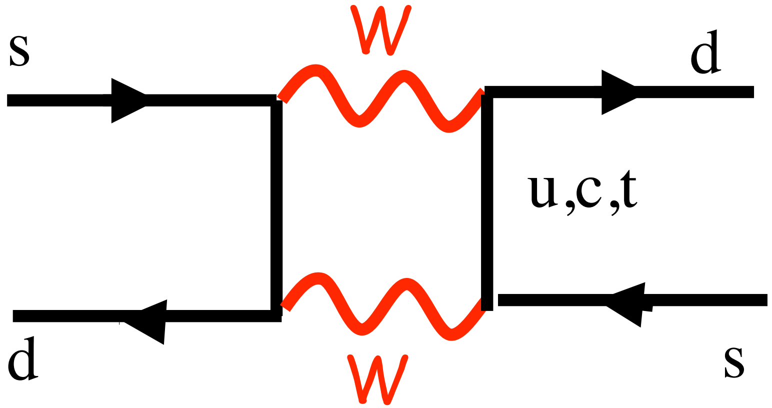
Indirect CP violation: mixing





ΔS=2





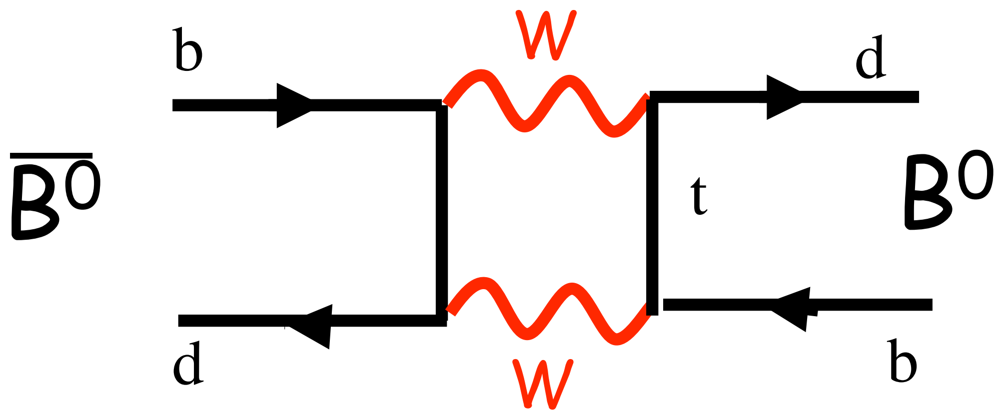
Box diagrams:
They are also responsible
for B^0 - $\bar{B}^0$ mixing
$\Delta m_{d,s}$

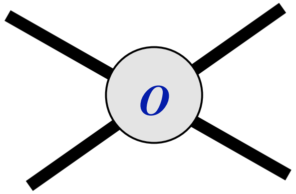
Complex ΔS=2 effective coupling

B^0 - B^0 mixing

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}$$

ΔB=2 Transitions



$\mathcal{H}_{eff}^{\Delta B=2} =$ 

$$\propto \left(\bar{\mathbf{d}}\, \gamma_\mu (\mathbf{1} - \gamma_5)\, \mathbf{b} \right)^2$$

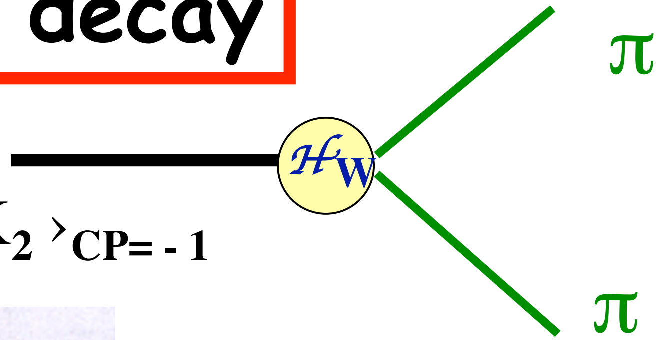
CKM

Hadronic matrix element

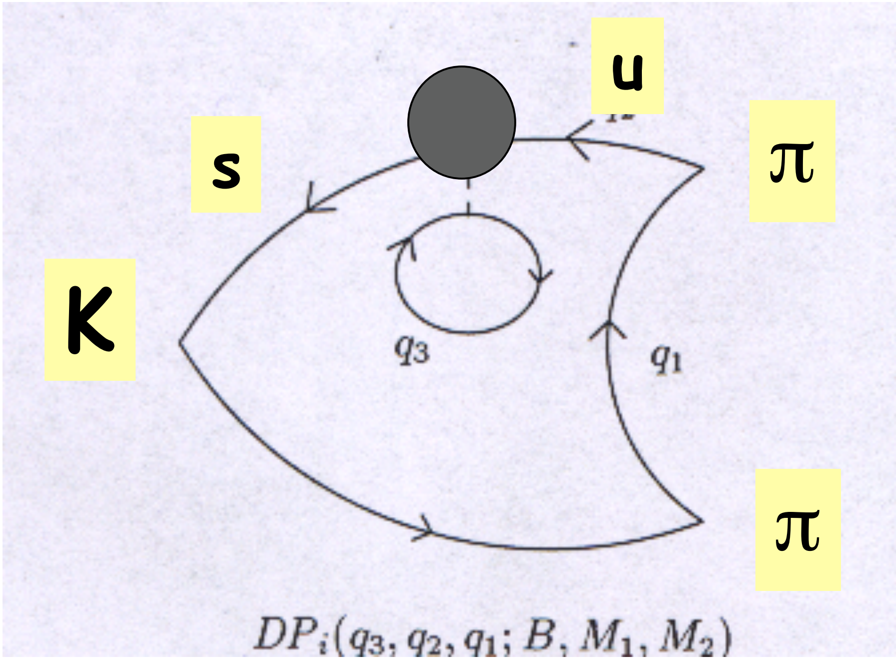
$$\Delta m_{d,s} = \frac{G_F^2 M_W^2}{16\pi^2} A^2 \lambda^6 F_{tt}\left(\frac{m_t^2}{M_W^2}\right) \langle O \rangle$$

Direct CP violation: decay

$|K_L\rangle = |K_2\rangle_{CP=-1}$



CP= + 1



S

Complex ΔS=1 effective coupling

$$\mathcal{L}^{C\!\!\!/P} = \mathcal{L}^{\Delta F=0} + \mathcal{L}^{\Delta F=1} + \mathcal{L}^{\Delta F=2}$$

ΔF=0 $d_e < 1.5\ 10^{-27}$ e cm $d_{\mathcal{N}} < 6.3\ 10^{-26}$ e cm

ΔF=1 $\varepsilon' / \varepsilon$

ΔF=2 ε and $B \to J/\psi\ K_s$

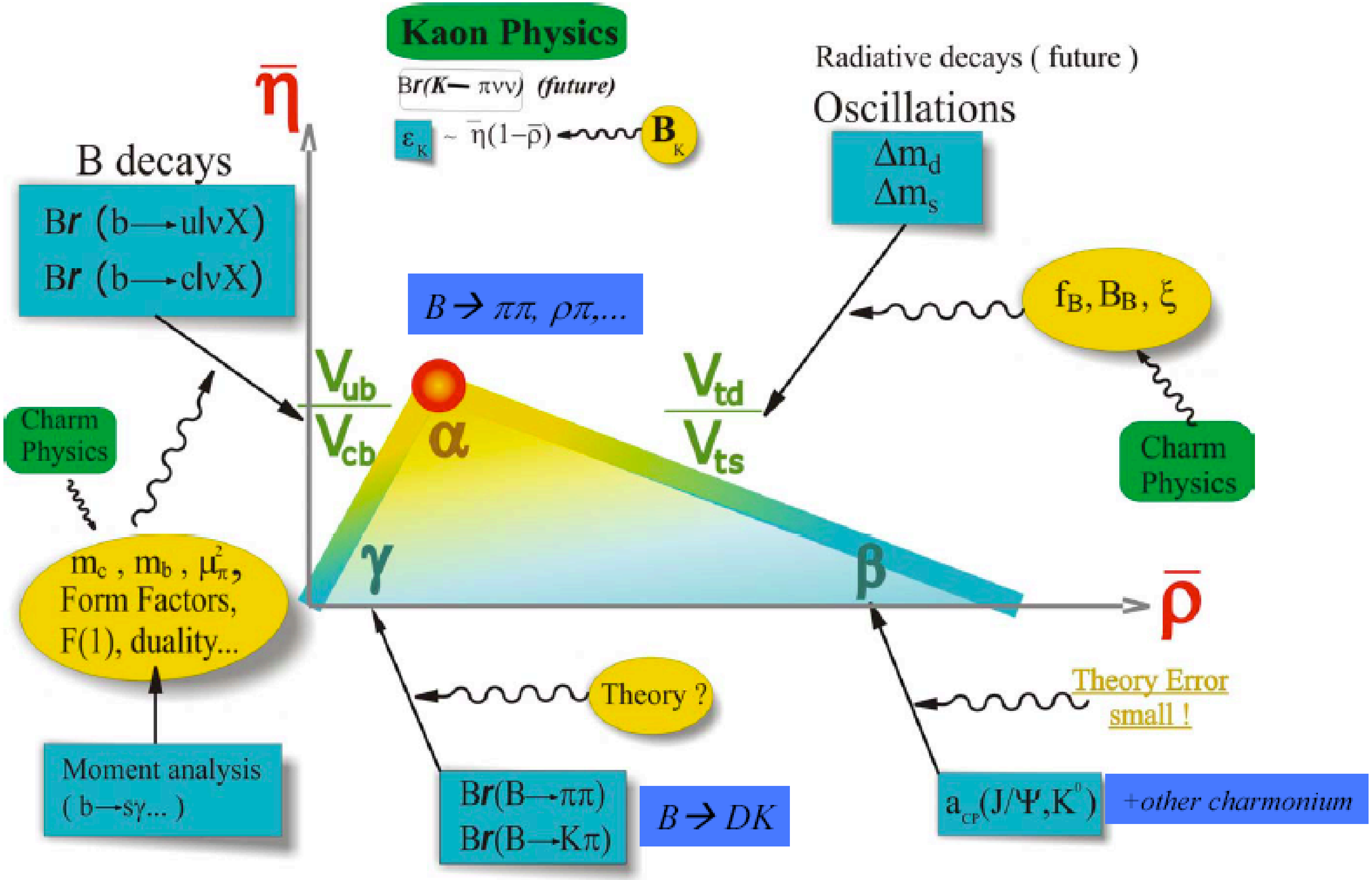
Observed Genuine FCNC

	Exp	Th
ε	$2.271 \pm 0.017\ 10^{-3}$	$\eta\ (1-\rho)\ B_K$
$\varepsilon\ '\ /\ \varepsilon$	$17.2 \pm 1.8\ 10^{-4}$	$-7 \div 30\ 10^{-4}$
$\Delta M_s\ /\ \Delta M_d$	17.77 ± 0.12 $0.507 \pm 0.005\ ps^{-1}$	$[(1-\rho)^2 + \eta^2]^{-1}\ \xi$
$BR(B \rightarrow X_s\ \gamma)$	$3.11 \pm 0.39\ 10^{-4}$	$3.50 \pm 0.50\ 10^{-4}$
$BR(K^+ \rightarrow \pi^+\ \nu\nu)$	$1.5\ {+3.4}{-1.2}\ 10^{-10}$	$0.8 \pm 0.3\ 10^{-10}$

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
$A_{CP}(B_d \to J/\psi\, K_s)$	$\sin 2\beta$	–

For details see:
UTfit Collaboration
hep-ph/0501199
hep-ph/0509219
hep-ph/0605213
hep-ph/0606167
http://www.utfit.org

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

classical UT analysis

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

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

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

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 $\Delta M_{d,s}$

$\Gamma(B \to c, u)$, $K^+ \to \pi^+ \nu \bar{\nu}$

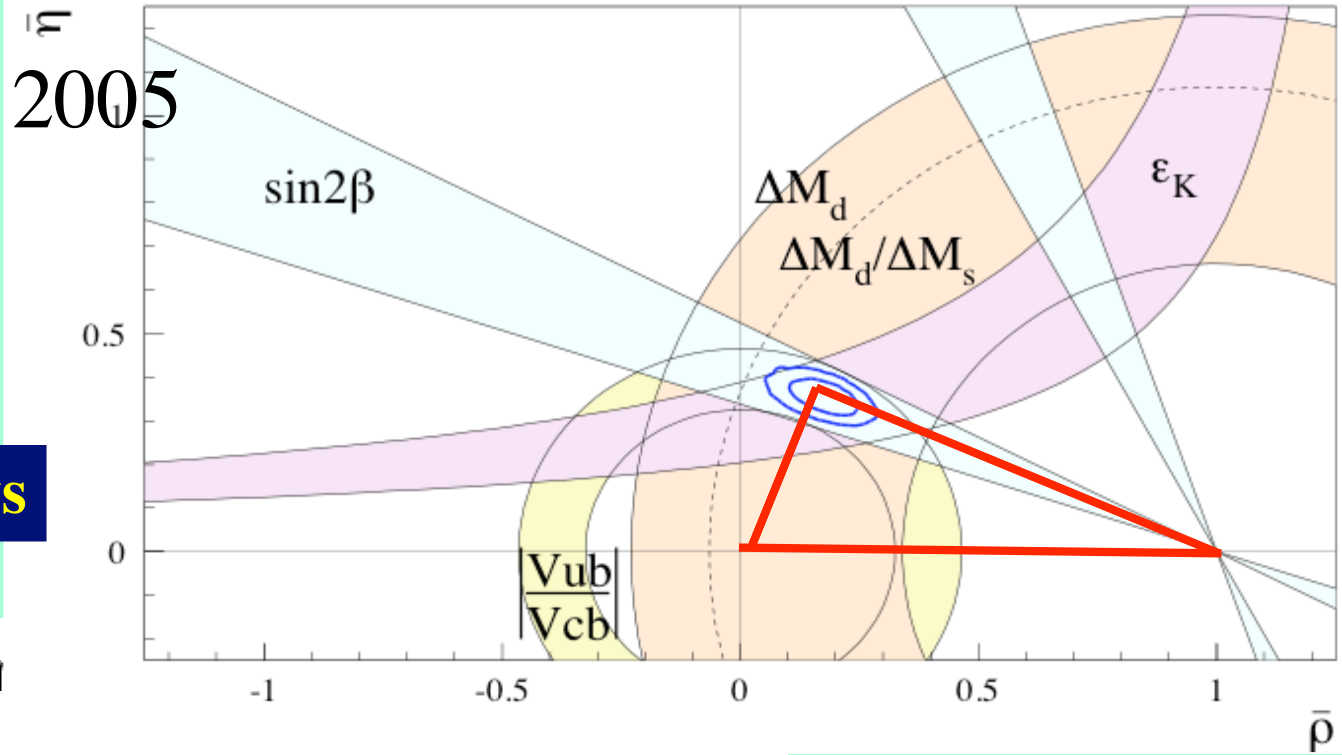
3) Third class quantities, for which theoretical predictions are model dependent (BBNS, charming, etc.)

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	$\lvert V_{td} \rvert^2 f_{B_d}^2 B_{B_d}$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert \frac{V_{td}}{V_{ts}} \right\rvert^2 \xi^2$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
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

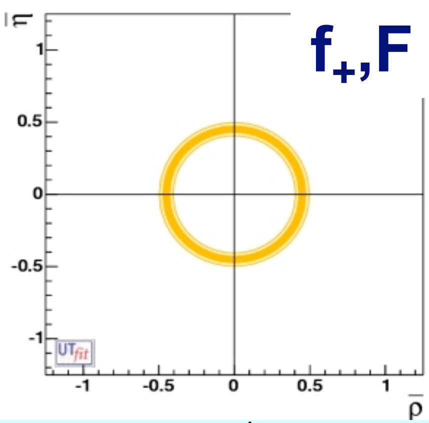
$B^0_{d,s}$ - $\overline{B}^0_{d,s}$ mixing

B_d Asymmetry

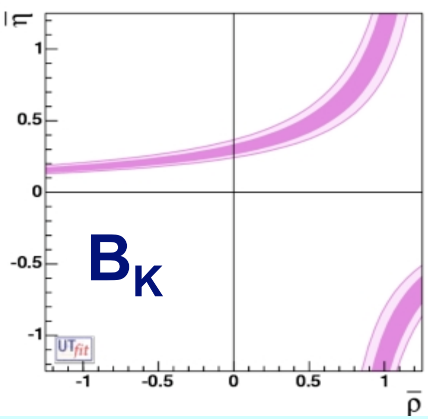
Classical Quantities used in the Standard UT Analysis

levels @
68% (95%) CL

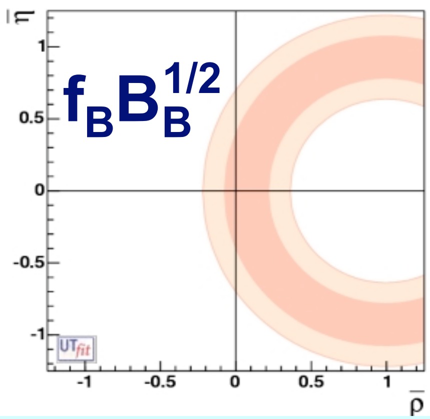
V_{ub}/V_{cb}



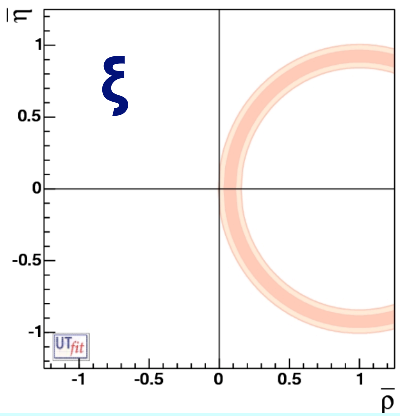
ε_K



Δm_d



$\Delta m_d/\Delta m_s$



UT-LATTICE

Inclusive vs Exclusive
Opportunity for lattice QCD
see later

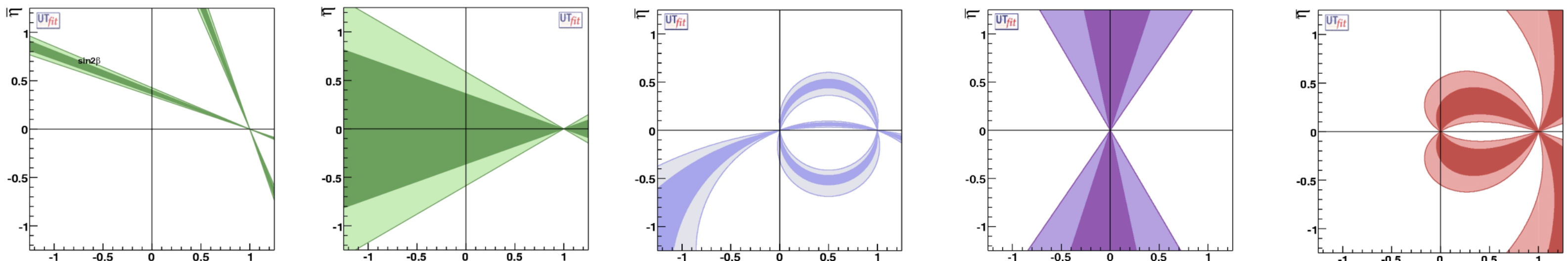
before
only a lower bound

New 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 | $\sin(2\beta+\gamma)$

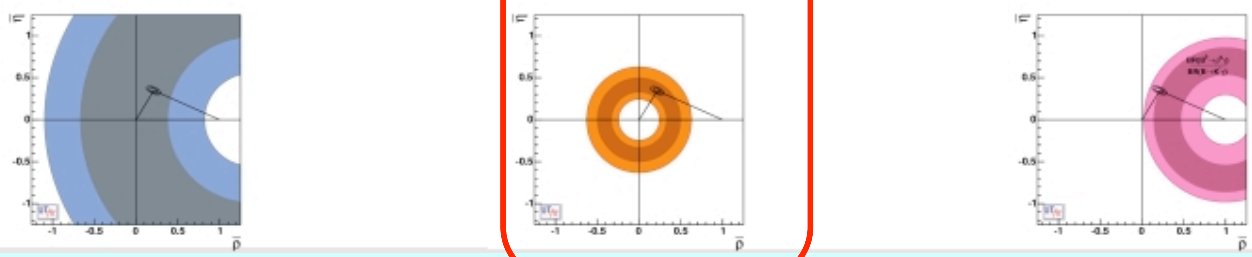


$B \to J/\Psi K^0$ | $B \to J/\Psi K^{*0}$ | $B \to \pi\pi, \rho\rho$ | $B \to D^{(*)}K$ | $B \to D^{(*)}\pi, D\rho$

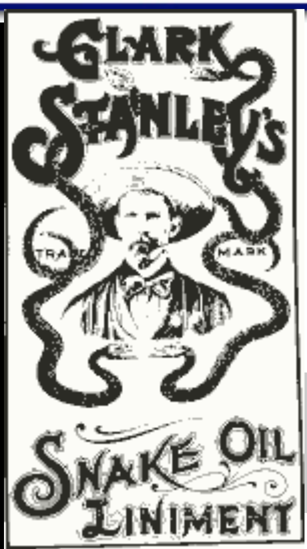
New Constraints from B and K rare decays (not used yet)

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.

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

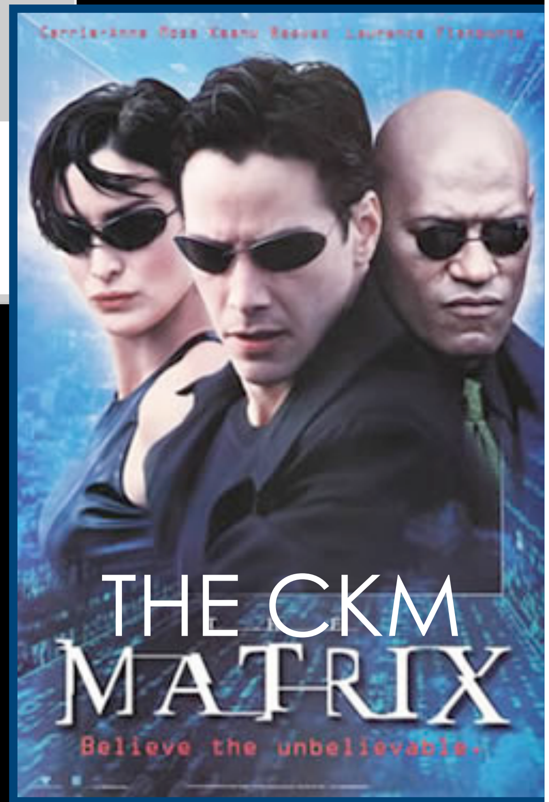


THE COLLABORATION



M.Bona, M.Ciuchini, E.Franco, V.Lubicz, G.Martinelli, F.Parodi, M.Pierini, P.Roudeau, C.Schiavi, L.Silvestrini, V. Sordini, A.Stocchi, V.Vagnoni

Roma, Genova, Annecy, Orsay, Bologna



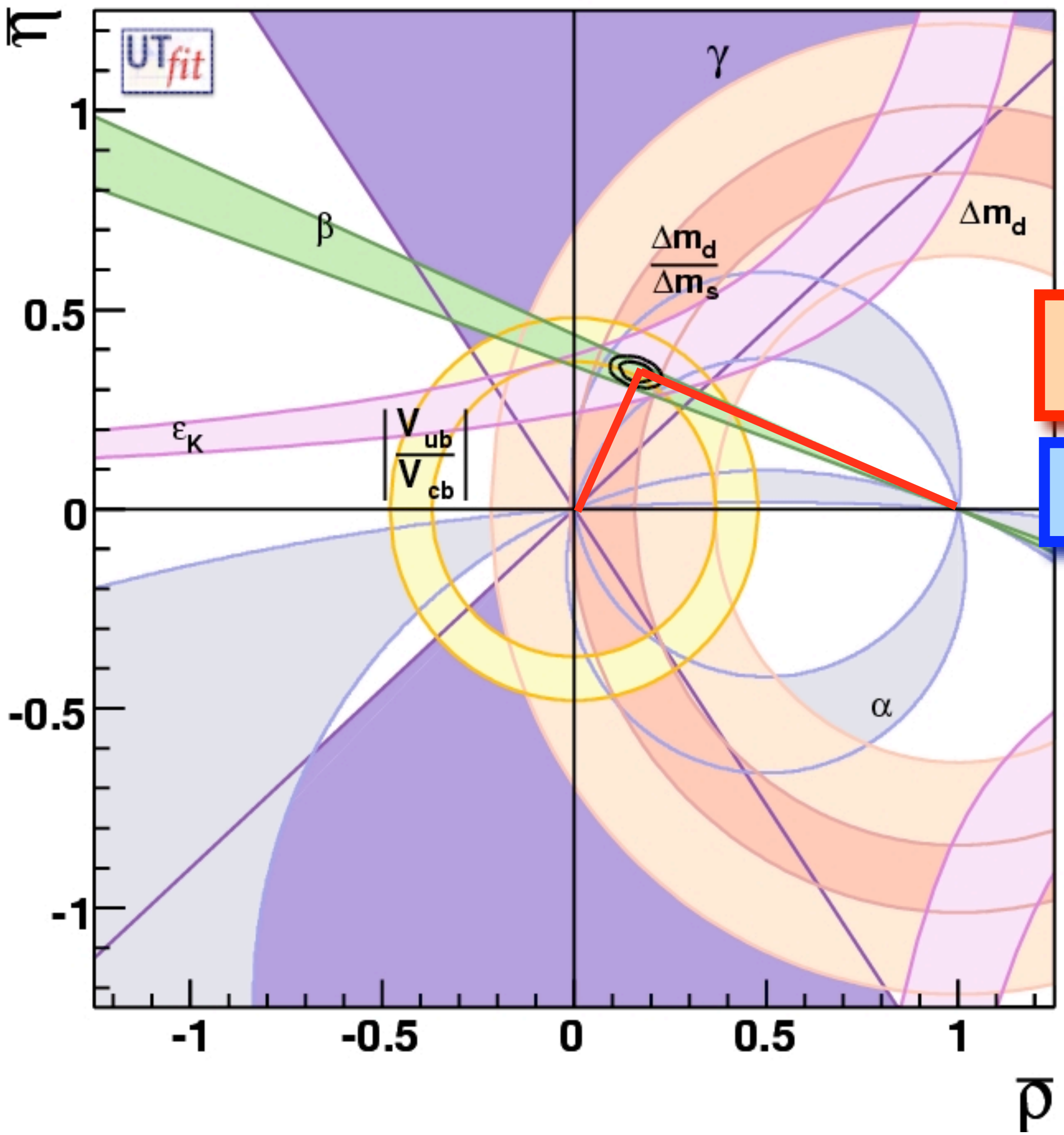
2006 ANALYSIS

- New quantities e.g. B -> DK included
- Upgraded exp. numbers (after ICHEP)
    - CDF & Belle new measurements

www.utfit.org

Results for ρ and η & related quantities

With the constraint fromΔm_s



contours @ 68% and 95% C.L.

$\rho = 0.147 \pm 0.029$

$\eta = 0.342 \pm 0.016$

$\alpha = (91 \pm 8)^0$

$\sin 2\beta = 0.690 \pm 0.023$

$\gamma = (66.7 \pm 6.4)^0$

A closer look to the analysis:

1) Predictions vs Postdictions
2) Lattice vs angles
3) V_{ub} inclusive, V_{ub} exclusive vs sin 2β
4) Experimental determination of lattice parameters

V_{UB} PUZZLE

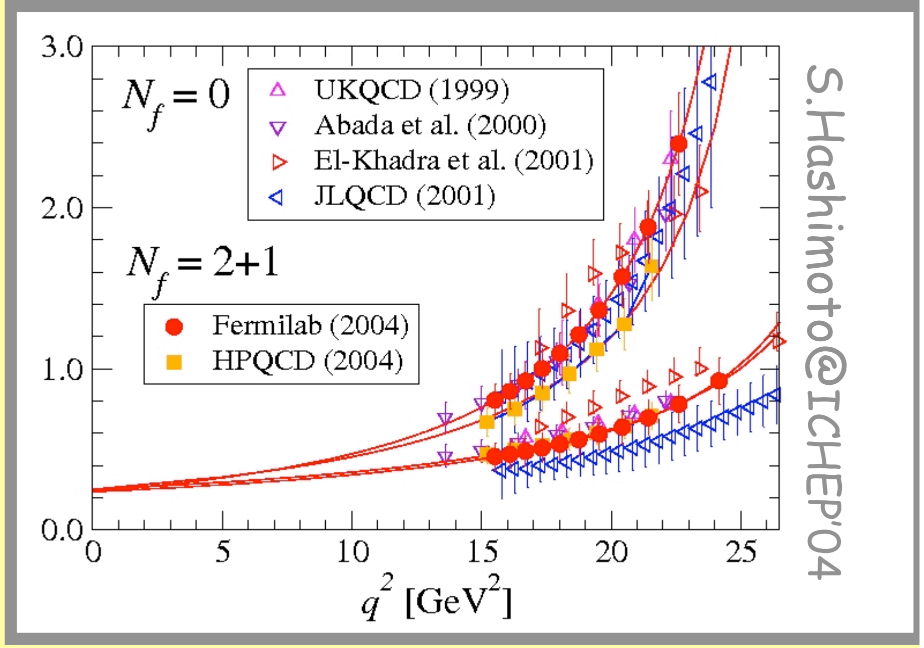
$\lvert V_{ub}\rvert \times 10^4$	excl.	35.0	4.0	Lattice QCDSR
$\lvert V_{ub}\rvert \times 10^4$	incl.	44.9	3.3	HQET+Model
$\lvert V_{ub}\rvert \times 10^4$	average	40.9	2.5	

Inclusive: uses non perturbative parameters most **not** from lattice QCD (fitted from the lepton spectrum)

$$\bar{\Lambda} \quad \lambda_1 \sim \frac{\bar{b}\vec{D}^2 b}{2m_b} \quad \lambda_2 \sim \frac{\bar{b}\sigma_{\mu\nu}G^{\mu\nu}b}{2m_b}$$

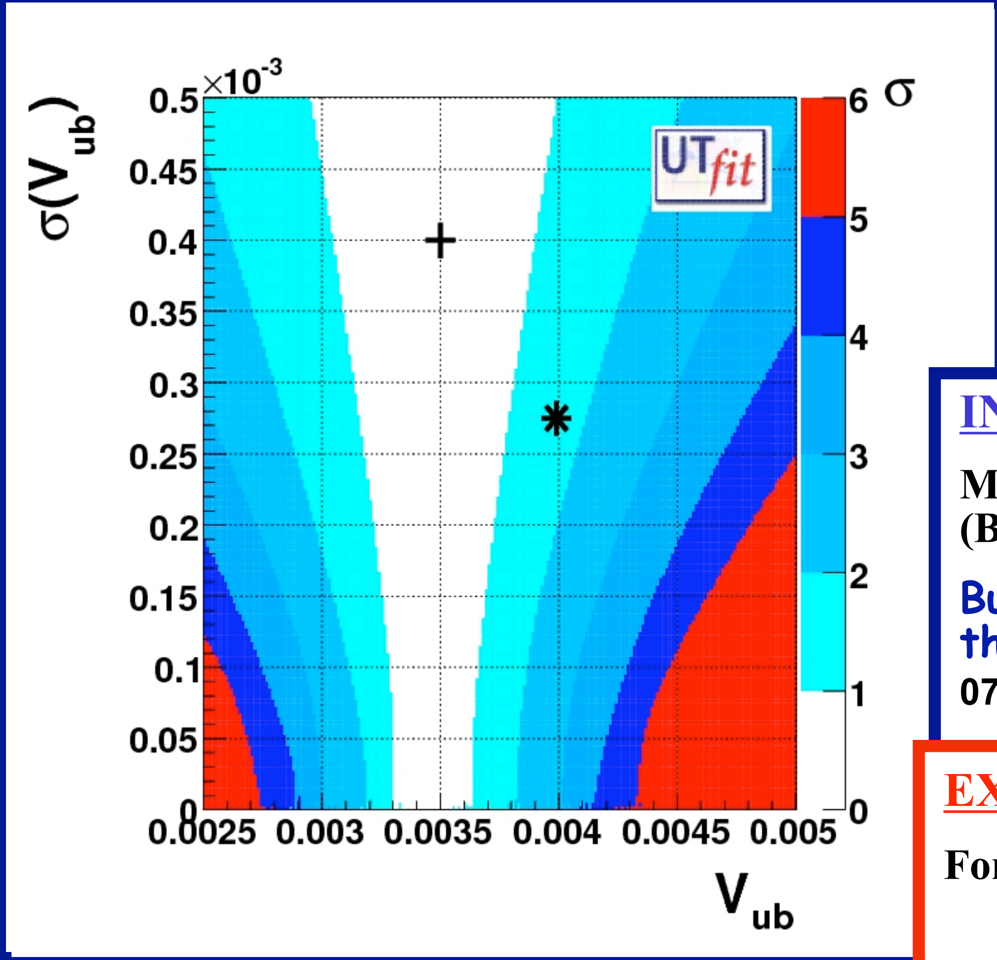
Exclusive: uses non perturbative form factors from LQCD and QCDSR

$$f^+(q^2) \quad V(q^2) \quad A_{1,2}(q^2)$$



Tension between inclusive Vub and the rest of the fit

Tension between inclusive Vub and the rest of the fit



<u>INCLUSIVE</u> $V_{ub} = (43.1 \pm 3.9)\ 10^{-4}$

Model dependent in the threshold region (BLNP, DGE, BLL)

But with a different modelling of the threshold region [U.Aglietti et al., 0711.0860] $V_{ub} = (36.9 \pm 1.3 \pm 3.9)\ 10^{-4}$

<u>EXCLUSIVE</u> $V_{ub} = (34.0 \pm 4.0)\ 10^{-4}$

Form factors from LQCD and QCDSR

V_{UB} PUZZLE

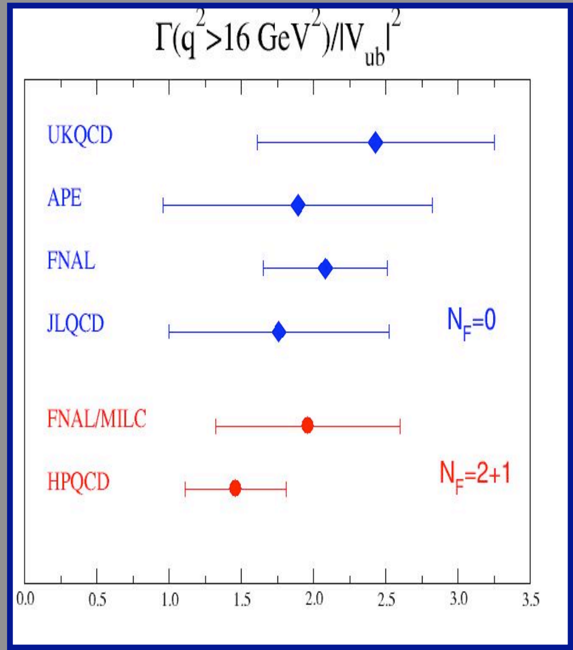
Khodjamirian

Recent $|V_{ub}|$ determinations from $B \to \pi l \nu_l$

[ref.]	$f^+_{B\pi}(q^2)$ calculation	$f^+_{B\pi}(q^2)$ input	$\lvert V_{ub}\rvert \times 10^3$
Okamoto et al.	lattice ($n_f = 3$)	-	3.78±0.25±0.52
HPQCD	lattice ($n_f = 3$)	-	3.55±0.25±0.50
Arnesen et al.	-	lattice⊕SCET	$3.54 \pm 0.17 \pm 0.44$
BecherHill	-	lattice	$3.7 \pm 0.2 \pm 0.1$
Flynn et al	-	lattice ⊕ LCSR	$3.47 \pm 0.29 \pm 0.03$
Ball, Zwicky	LCSR	-	$3.5 \pm 0.4 \pm 0.1$
this work	LCSR	-	$3.5 \pm 0.4 \pm 0.2 \pm 0.1$

V_{UB} PUZZLE

LATTICE QCD:
improve V_{ub} excl. to solve the tension



Beneke CERN '08

$|V_{ub}|$ crisis (about to be resolved?)

- $|V_{ub}| f_+^{B\pi}(0) = (9.1 \pm 0.6 \pm 0.3) \times 10^{-4}$ from semileptonic $B \to \pi l \nu$ spectrum + form factor extrapolation (Ball, 2006)
  Also lattice results (HPQCD) tend to small values.
- $|V_{ub}| f_+^{B\pi}(0) = (8.1 \pm 0.4\,(?)) \times 10^{-4}$ from $B \to \pi^+\pi^-, \pi^+\pi^0, \pi\rho, \ldots$ + factorization
  (MB, Neubert, 2003; Arnesen et al, 2005; MB, Jäger, 2005)

$\Longrightarrow$ $|V_{ub}| \simeq 3.5 \times 10^{-4}$, in contrast to determination from moments of inclusive $b \to u\ell\nu$ decay, which was $|V_{ub}| \simeq (4.5 \pm 0.3) \times 10^{-4}$.

But: according to (Neubert, LP07) $|V_{ub}| \simeq (3.7 \pm 0.3) \times 10^{-4}$ after reevaluation of m_b input and omitting $B \to X_s\gamma$ moments!

Hadronic Parameters From UTfit

1) Predictions vs Postdictions
2) Lattice vs angles
3) V_{ub} inclusive, V_{ub} exclusive vs sin 2β
4) Experimental determination of lattice parameters

IMPACT of the NEW MEASUREMENTS on LATTICE HADRONIC PARAMETERS

$$f_{B_s} \hat{B}_{B_s}^{1/2} \quad \xi \quad \hat{B}_K$$

Comparison between experiments and theory

Comparison between experiments and theory

exps vs predictions

$f_{Bs}\sqrt{B_{Bs}} = 270 \pm 30$ MeV

lattice

$f_{Bs}\sqrt{B_{Bs}}=265 \pm 4$ MeV

UTA 2% ERROR !!

$\xi = 1.25 \pm 0.06$ **UTA**

$\xi = 1.21 \pm 0.04$

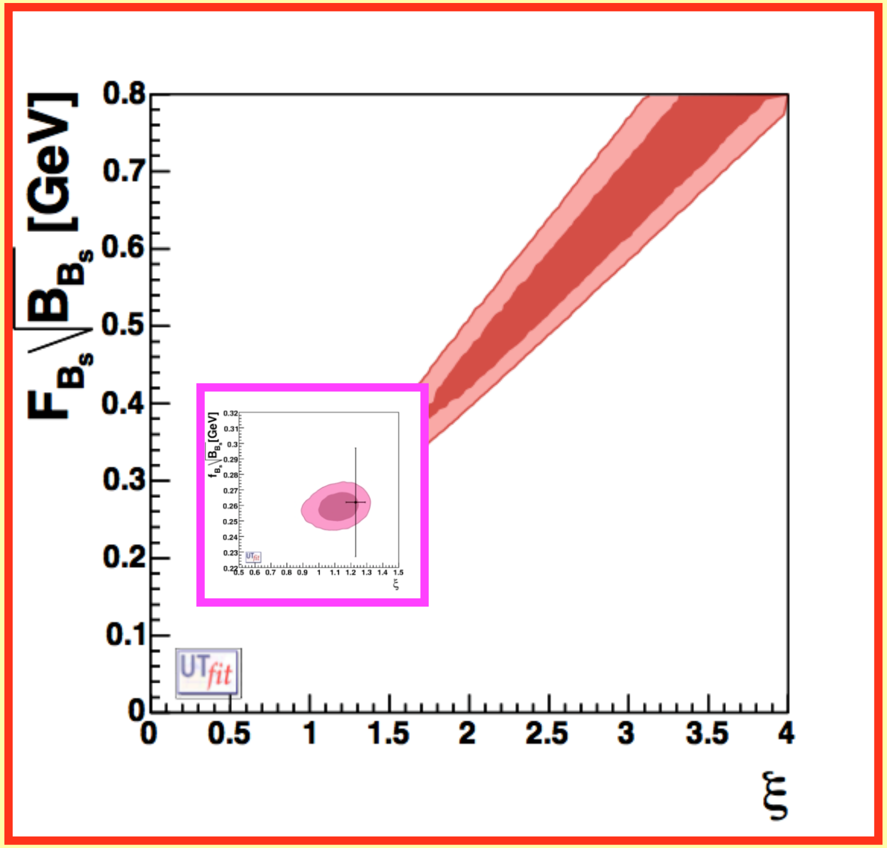
lattice

$B_K = 0.75 \pm 0.07$

$B_K = 0.75 \pm 0.07$

V. Lubicz and C. Tarantino 0807.4605

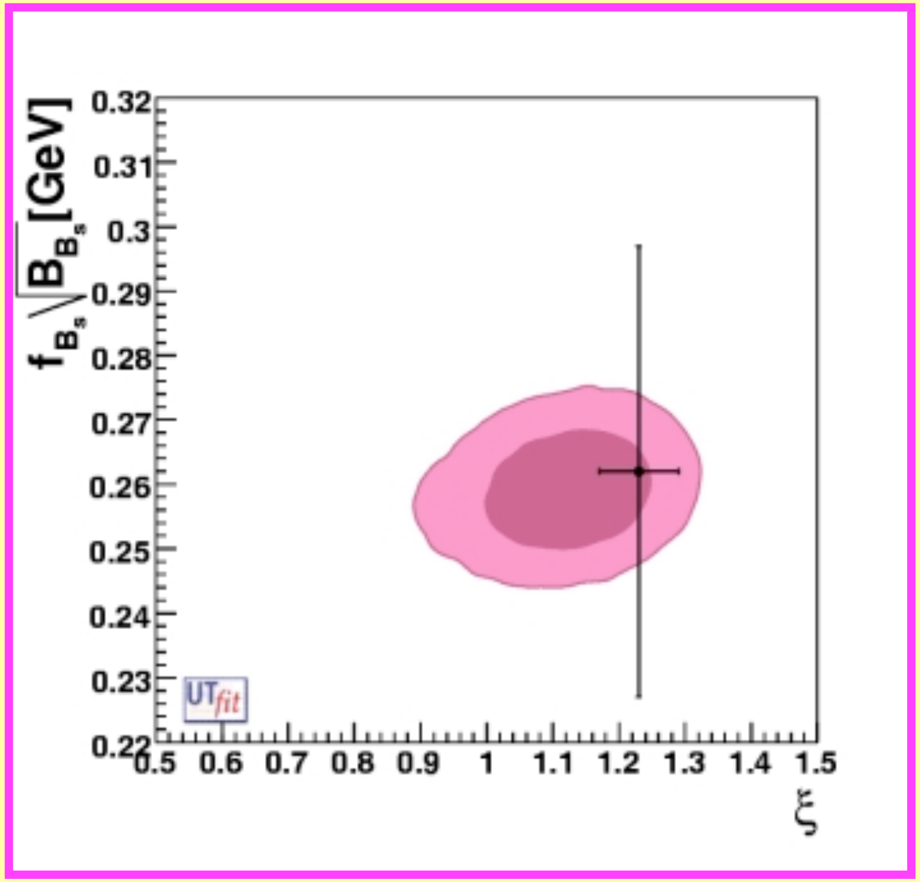
SPECTACULAR AGREEMENT (EVEN WITH QUENCHED LATTICE QCD)



$F_{B_s}\sqrt{B_{B_s}}$ [GeV]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 0.5 1 1.5 2 2.5 3 3.5 4
ξ
UTfit

OLD

NEW



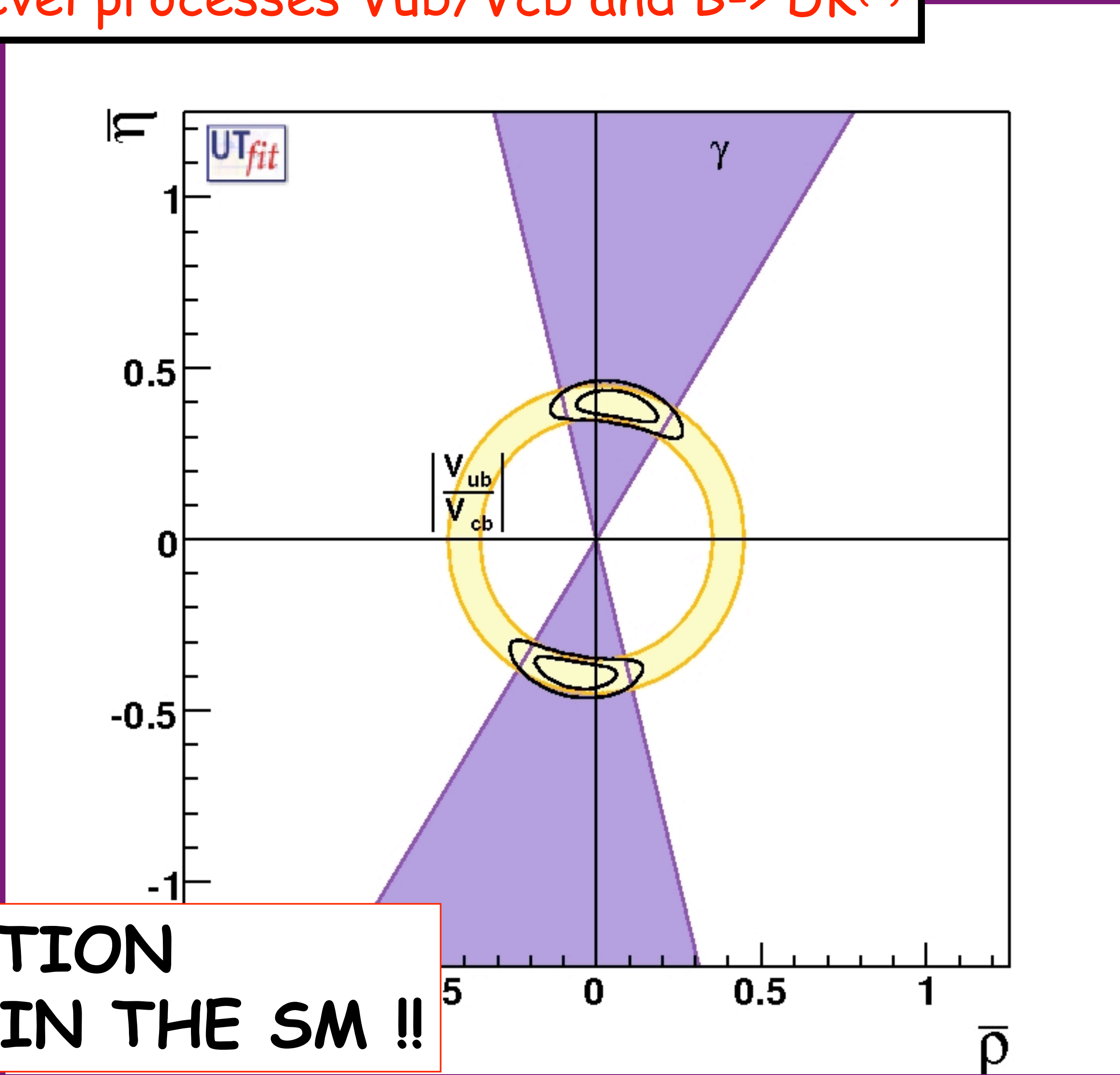
$f_{B_s}\sqrt{B_{B_s}}$ [GeV]
0.32
0.31
0.3
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
ξ
UTfit

…. beyond the Standard Model

~~CP~~ beyond the SM (Supersymmetry)

Spin	SM particles		Spin	Superpartners
Spin 1/2	Quarks q_L, u_R, d_R; Leptons l_L, e_R	⟷	Spin 0	SQuarks Q_L, U_R, D_R; SLeptons L_L, E_R
Spin 1	Gauge bosons W, Z, γ, g	⟷	Spin 1/2	Gauginos $\tilde{w}, \tilde{z}, \tilde{\gamma}, \tilde{g}$
Spin 0	Higgs bosons H_1, H_2	⟷	Spin 1/2	Higgsinos $\tilde{H}_1, \tilde{H}_2$

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



CP VIOLATION PROVEN IN THE SM !!

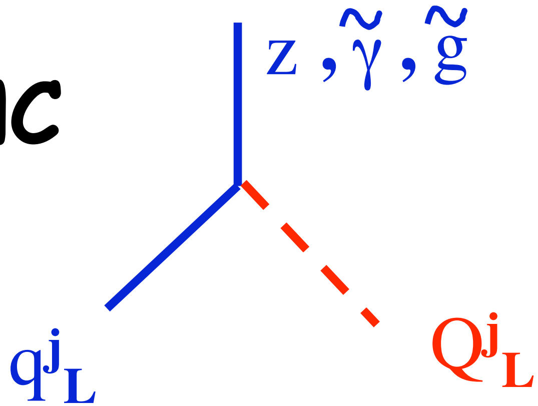
$$Q^{EXP} = V_{CKM}\langle F|\hat{O}|I\rangle$$

$$Q^{EXP} = \sum_i C^i_{SM}(M_W, m_t, \alpha_s)\langle F|\hat{O}_i|I\rangle + \sum_{i'} C^{i'}_{Beyond}(\tilde{m}_\beta, \alpha_s)\langle F|\hat{O}_{i'}|I\rangle$$

In general the mixing mass matrix of the SQuarks (SMM) is not diagonal in flavour space analogously to the quark case We may either

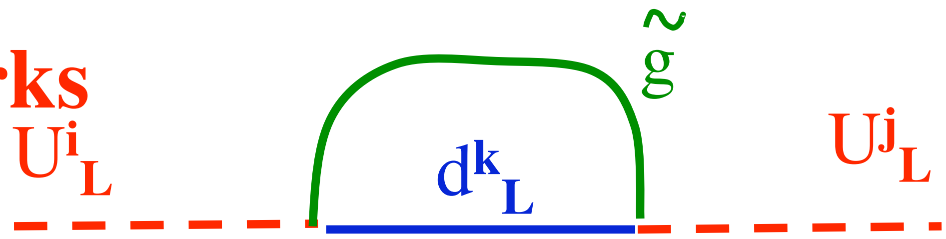
Diagonalize the SMM

FCNC

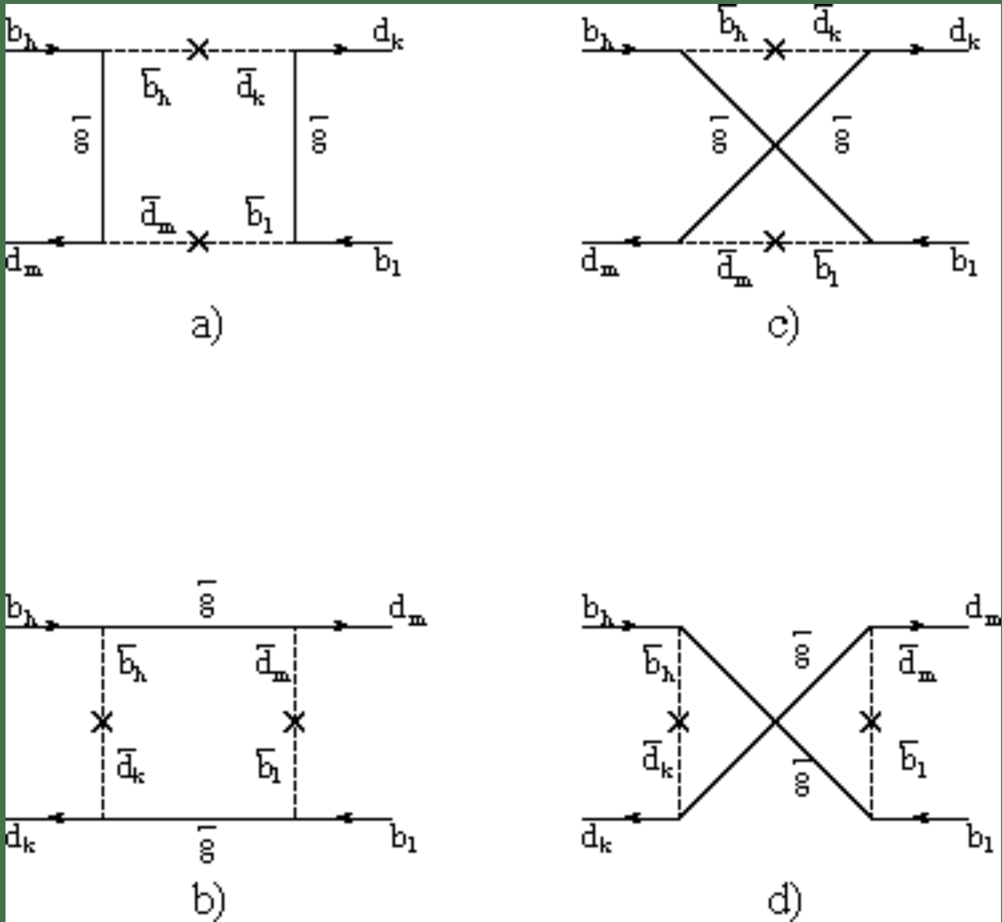


or Rotate by the same matrices the SUSY partners of the u- and d- like quarks

$(Q^j_L)' = U^{ij}_L \, Q^j_L$



In the latter case the Squark Mass Matrix is not diagonal



$$(\tilde{m}^2_Q)_{ij} = \tilde{m}^2_{average}\, 1_{ij} + \Delta\tilde{m}_{ij}^2 \qquad \delta_{ij} = \Delta\tilde{m}_{ij}^2 / \tilde{m}^2_{average}$$

New local four-fermion operators are generated

$Q_1 = (\bar{s}_L^A \gamma_\mu d_L^A)(\bar{s}_L^B \gamma_\mu d_L^B)$ SM

$Q_2 = (\bar{s}_R^A d_L^A)(\bar{s}_R^B d_L^B)$

$Q_3 = (\bar{s}_R^A d_L^B)(\bar{s}_R^B d_L^A)$

$Q_4 = (\bar{s}_R^A d_L^A)(\bar{s}_L^B d_R^B)$

$Q_5 = (\bar{s}_R^A d_L^B)(\bar{s}_L^B d_R^A)$

+ those obtained by $L \leftrightarrow R$

Similarly for the b quark e.g.

$(\bar{b}_R^A d_L^A)(\bar{b}_R^B d_L^B)$

B_s mixing , a road to New Physics (NP) ?

The Standard Model contribution to CP violation in B_s mixing is well predicted and rather small

- $\sin 2\beta_s = 0.037 \pm 0.002$ (SM or MFV)
- $\sin 2\beta_s = 0.041 \pm 0.004$ (Arbitrary NP)

The phase of the mixing amplitudes can be extracted from $B_s \to J/\Psi\ \varphi$ with a relatively small th. uncertainty. A phase very different from 0.04 implies **NP in B_s mixing**

Main Ingredients and General Parametrizations

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

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

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

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

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

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

SM	→	SM+NP
$(V_{ub}/V_{cb})^{SM}$ γ^{SM}	**tree level**	$(V_{ub}/V_{cb})^{SM}$ γ^{SM}
β^{SM} α^{SM} Δm_d	***Bd Mixing***	$\beta^{SM}+\phi_{Bd}$ $\alpha^{SM}-\phi_{Bd}$ $C_{Bd}\Delta m_d$
Δm_s^{SM} $-\beta_s^{SM}$	***Bs Mixing***	$C_{Bs}\Delta m_s^{SM}$ $-\beta_s^{SM}+\phi_{Bs}$
ε_K^{SM} Δm_K^{SM}	***K Mixing***	$C_{\varepsilon_K}\,\varepsilon_K^{SM}$ $C_{\Delta mK}\,\Delta m_K^{SM}$

Physical observables

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

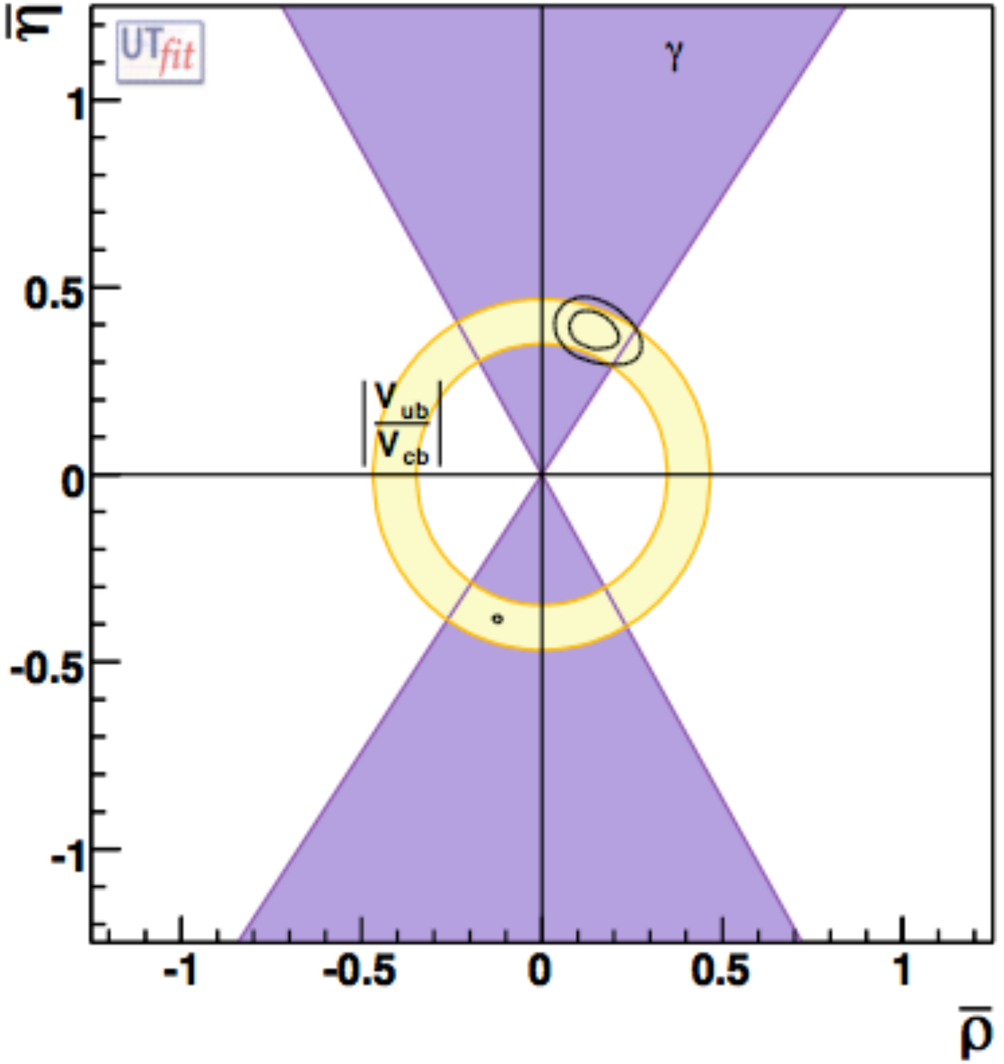
$$2\phi_s = -\arg A_s = 2\,(\beta_s - \phi_{B_s})$$

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

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

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

Utfit 0707.0636

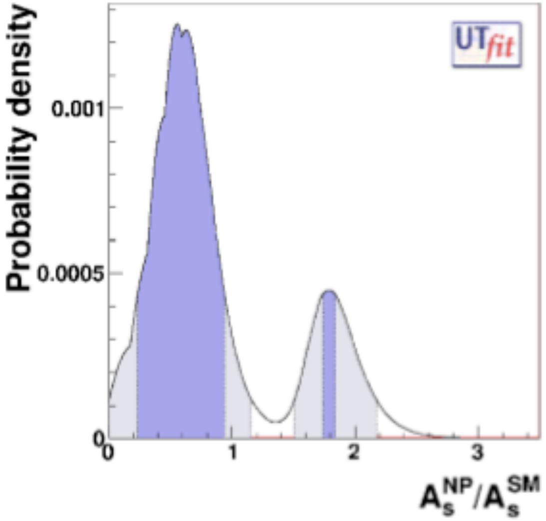


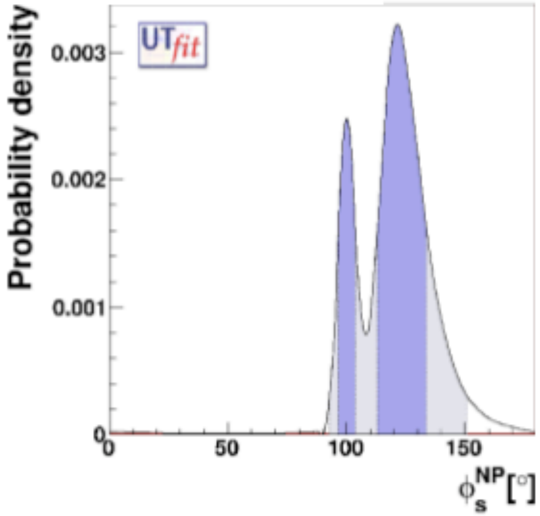
The two solutions for ϕ_s correspond to two regions for A_s^{NP} and ϕ_s^{NP}:

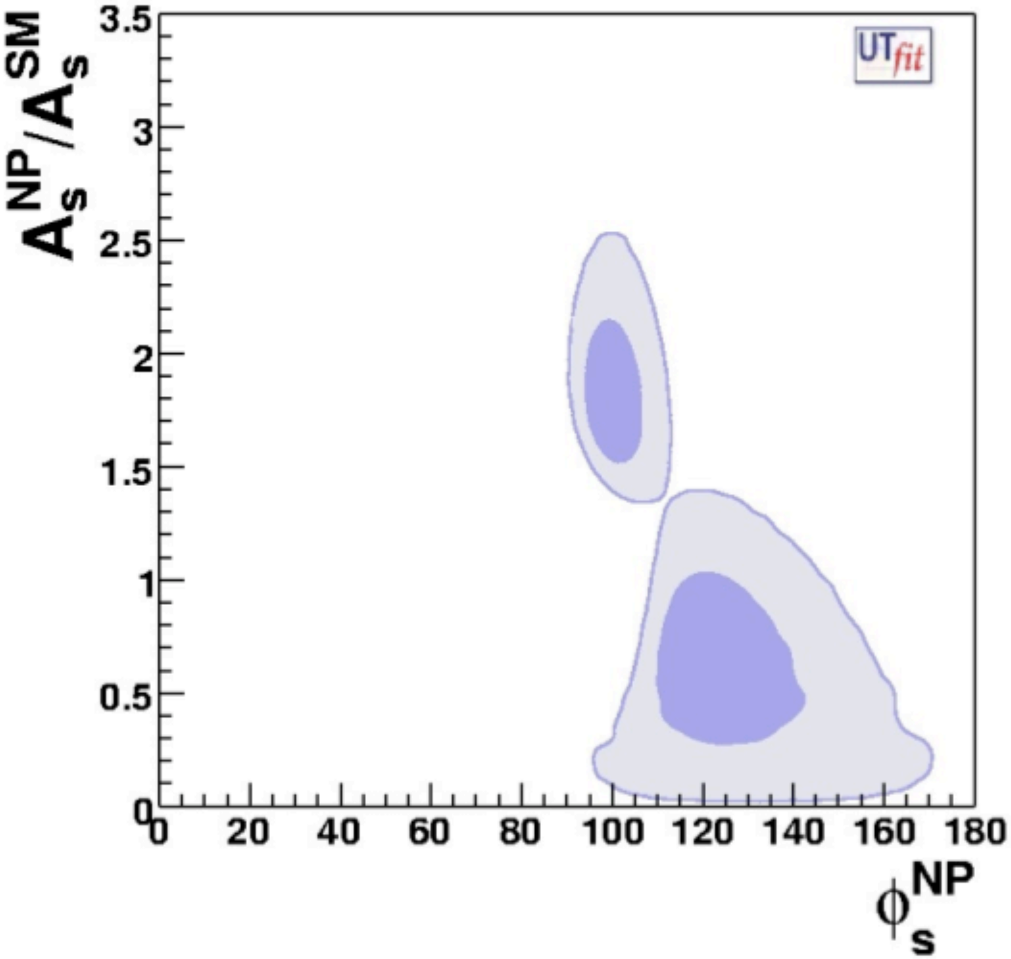
$A_s^{NP}/A_s^{SM}=0.6\pm0.4$ & $\phi_{NP}=(123\pm10)^\circ$

$A_s^{NP}/A_s^{SM}=1.8\pm0.1$ & $\phi_{NP}=(100\pm3)^\circ$

requires NP with new sources of CP violation!



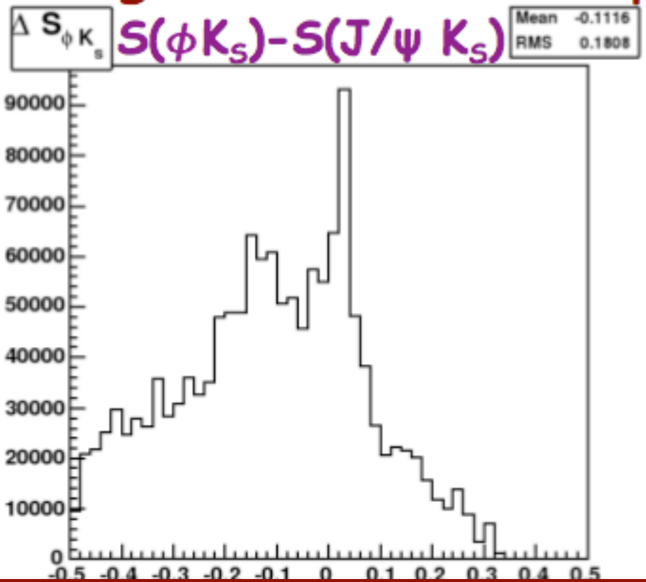


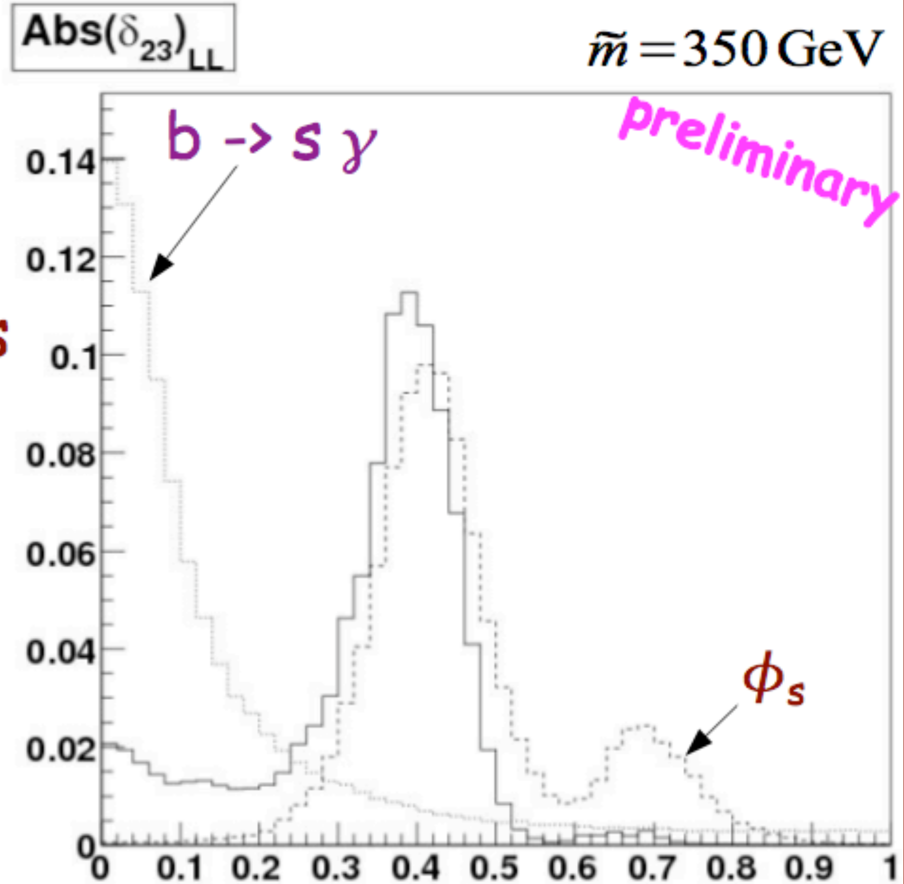


* chirality-flipping mass insertions are strongly bounded by $b \to s\,\gamma$: they are too small to produce the measured ϕ_s

<u>case #1</u>: single mass insertion, e.g. $(\delta_{23})_{LL}$

* large MI needed for ϕ_s: tension with $b \to s\,\gamma$
* MI saturates at 1: upper bound $\tilde{m}$ < O(1 TeV)
* huge effect in b->s penguins

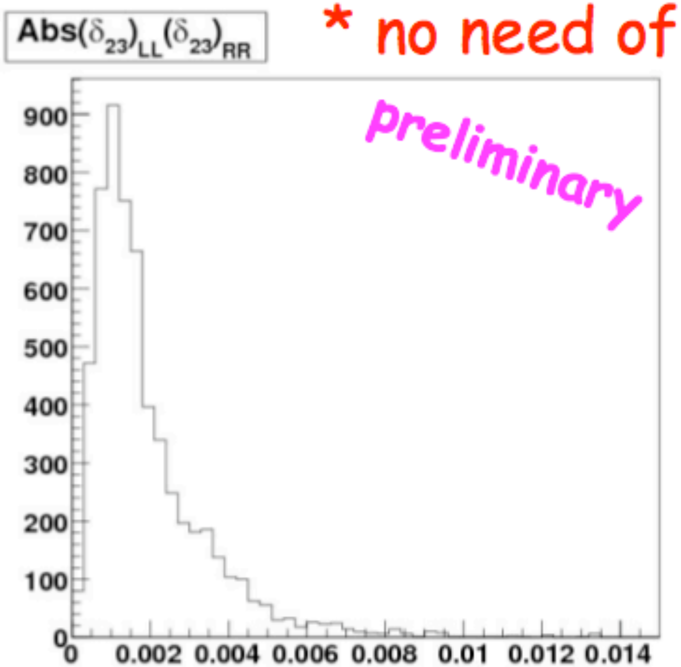


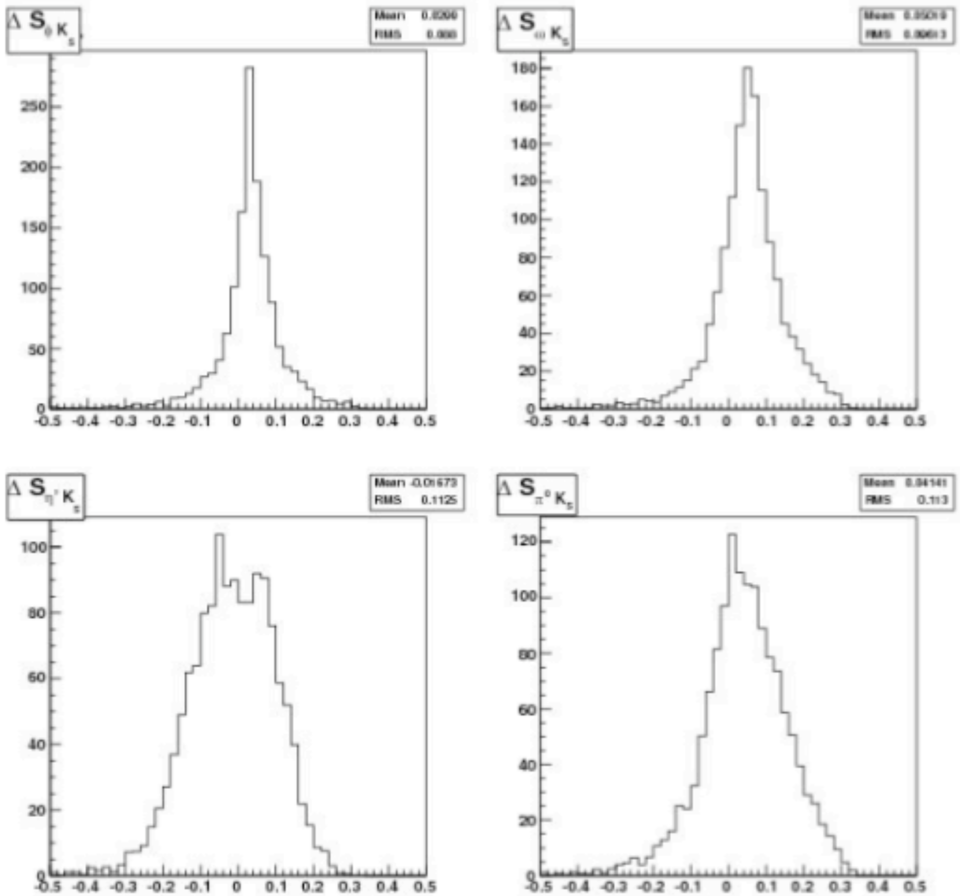


case #2: double mass insertion, $(\delta_{23})_{LL}$ & $(\delta_{23})_{RR}$

* no need of large MIs: $(\delta_{23})_{LL} \sim (\delta_{23})_{RR} \sim 3\text{-}4 \cdot 10^{-2}$

b -> s γ is no longer a problem





* large effects in b->s penguins still possible (larger if LR MIs are also switched on)

$b \to s$ & $\tau \to \mu\gamma$ in SUSY GUTS

When SUSY is broken at a scale larger than M_{GUT} SQuark and SLepton masses unify including the non-diagonal coupling $(\delta_{ij})_{LL}$, $(\delta_{ij})_{RR}$

The following relations holds at M_Z (Ciuchini et al. hep-ph/0307191)

$$(\delta^d_{ij})_{RR} \simeq \frac{m^2_L}{m^2_D}(\delta^l_{ij})_{LL}$$

$$(\delta^{u,d}_{ij})_{LL} \simeq \frac{m^2_E}{m^2_Q}(\delta^l_{ij})_{RR}$$

$$(\delta^u_{ij})_{RR} \simeq \frac{m^2_E}{m^2_U}(\delta^l_{ij})_{LL}$$

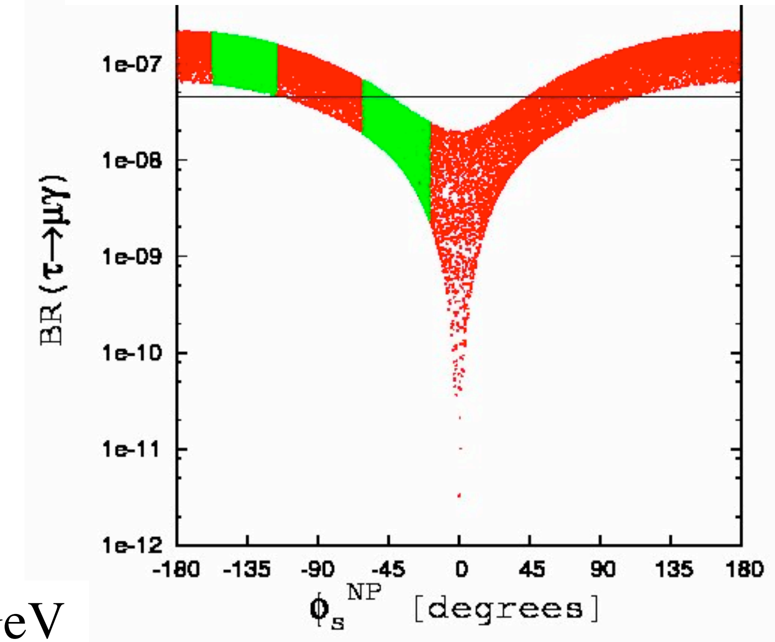
$$(\delta^d_{ij})_{LR} \simeq \frac{m^2_{L_{ave}}}{m^2_{Q_{ave}}}\frac{m_b}{m_\tau}(\delta^l_{ij})^*_{RL}$$

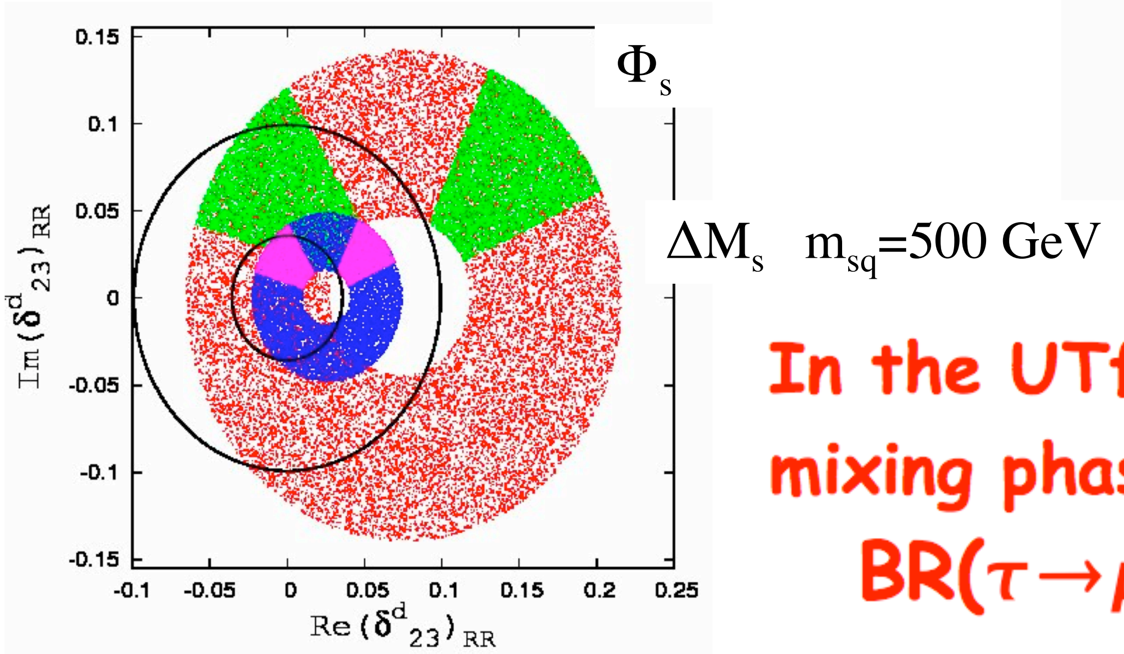
$b \rightarrow s$ & $\tau \rightarrow \mu\gamma$ in SUSY GUTS

mass insertion analysis in a SUSY-GUT scheme

* RG-induced $(\delta_{23})_{LL}$
* explicit $(\delta_{23})_{RR}$

Limits from Belle and Babar < 4.5 & 6.8 10^{-8}

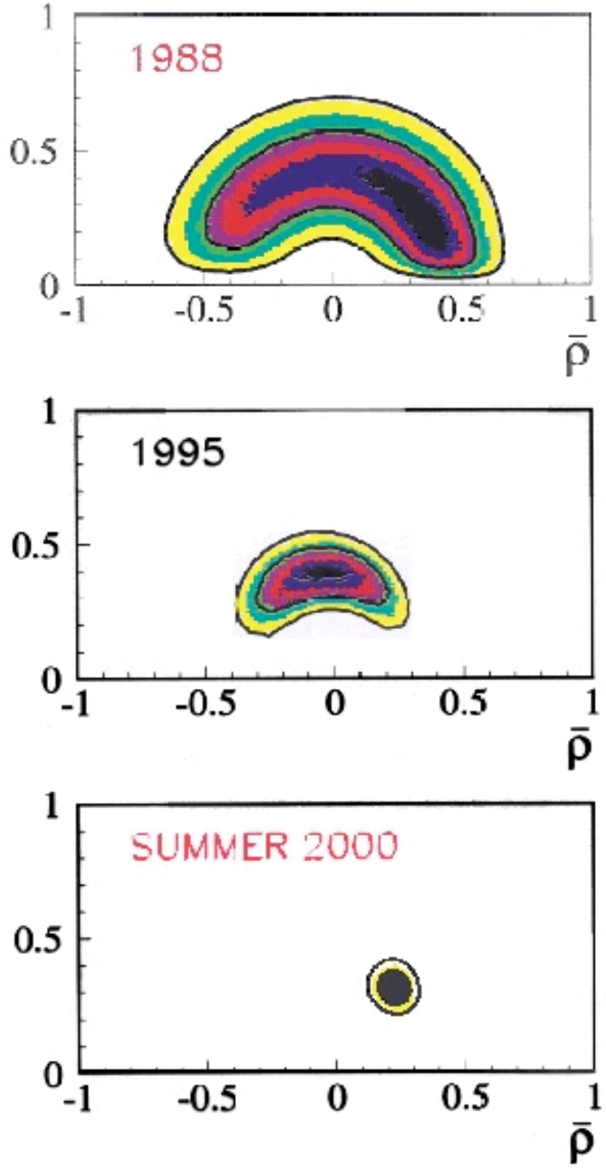




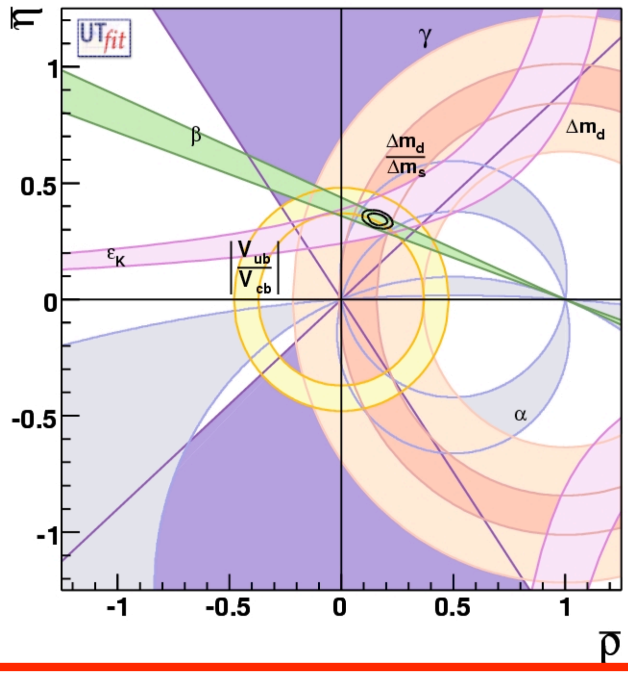
In the UTfit range for the B_s mixing phase:

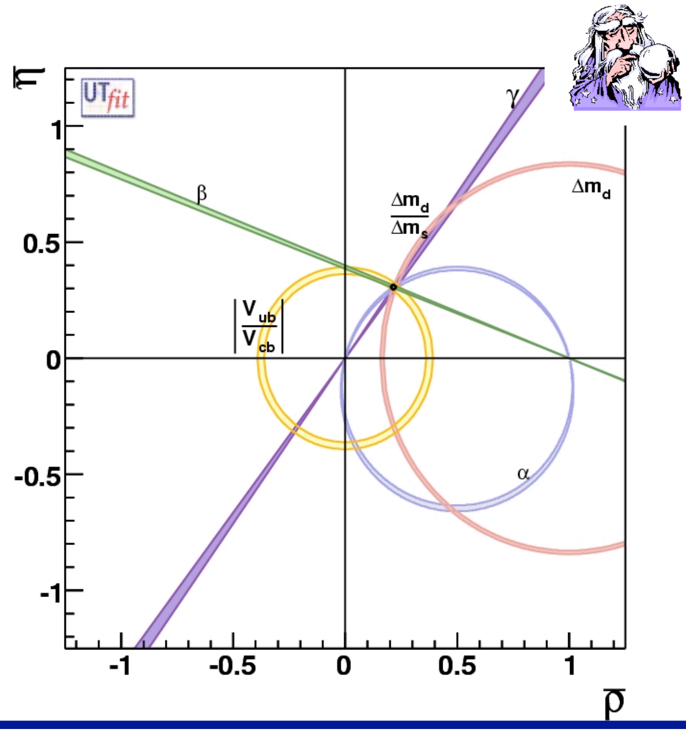
$BR(\tau \rightarrow \mu\gamma) > 3 \times 10^{-9}$!!

CONCLUSIONS: THANKS TO EXPERIMENTAL MEASUREMENTS & IMPROVED LATTICE CALCULATIONS



UTA in the SM: 2007 vs 2015





$\sigma(\bar{\rho})$ / $\bar{\rho}$ = 20%

$\sigma(\bar{\rho})$ / $\bar{\rho}$ = 1.3%

$\sigma(\bar{\eta})$/ $\bar{\eta}$ = 4.7%

$\sigma(\bar{\eta})$/ $\bar{\eta}$ = 0.8%

CONCLUSIONS

The evidence (strong suggestion, hint, ..) of a large Bs mixing phase survives to a second run of measurements

The upgraded UTFit analysis gives a 2.9 σ deviation from the SM (new CDF measurements still to be included)

In this framework MFV ruled out; MSSM could work with LL and RR insertions without conflict with b -> s γ

Within SUSY GUT a large BR(τ -> $\mu\gamma$) is expected