

Fisica del sapore e QCD sul reticolo

Vittorio
Lubicz



Sestri Levante 2009
Convegno Informale di
Fisica Teorica



Sestri Levante, 8-10 Giugno 2009

OUTLINE:

- The “precision era” of lattice QCD
- The first row unitarity test

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Lattice QCD: f_K/f_π and $f_+(0)$

- The Unitarity Triangle Analysis

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

LQCD: B_K , $f_{B(s)}$, $f_{D(s)}$, $G(1)^{B \rightarrow D^*}$, ...

- Flavour physics analysis in and beyond the Standard Model

In the era of precision experimental flavour physics

ϵ_K	$(2.280 \pm 0.013) 10^{-3}$	0.6%
Δm_d	$(0.507 \pm 0.005) \text{ ps}^{-1}$	1%
Δm_s	$(17.77 \pm 0.12) \text{ ps}^{-1}$	0.7%
$\text{Sin}2\beta$	0.668 ± 0.026	4%
$ V_{us} f_+(0)$	0.21661 ± 0.00047	0.2%
...

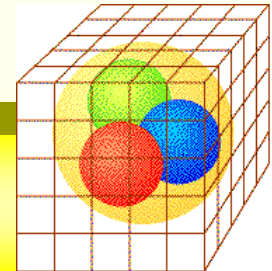


...

... ..

we are also entering the era of

Precision LATTICE QCD



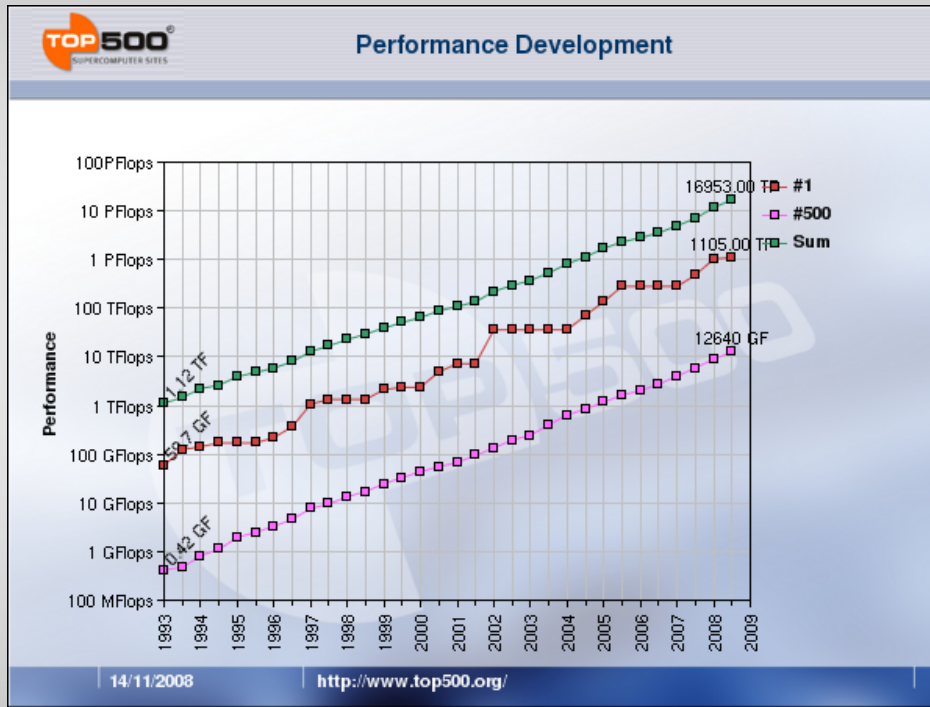
Unquenched calculations with relatively low quark masses are now being performed by several groups using different approaches (lattice action, renormalization,...).

Crucial when aiming at a percent precision.

"PRECISION" LATTICE QCD: WHY NOW

1) Increasing of computational power
 → Unquenched simulations

The Moore's Law



For Lattice QCD
 collab.ns today:
 ~ 1-20 TFlops

TeraFlops machines
 are required to
 perform unquenched
 simulations

CPU cost for $N_f=2$ Wilson fermions:

[Del Debbio et al. 2006]

$$\text{TFlops-years} \approx 0.15 \left(\frac{N_{\text{conf}}}{100} \right) \left(\frac{L_s}{3 \text{ fm}} \right)^5 \left(\frac{L_t}{2L_s} \right) \left(\frac{0.15}{\hat{m} / m_s} \right) \left(\frac{0.08 \text{ fm}}{a} \right)^6$$

2) Algorithmic improvements: → Light quark masses in the ChPT regime

“The Berlin wall has been disrupted”

CPU cost (for $N_f=2$ Wilson fermions):

Ukawa 2001 (The Berlin wall):

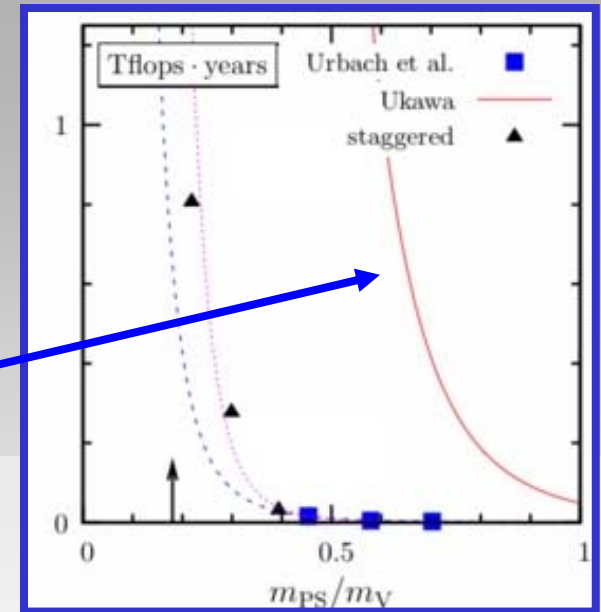
$$\text{TFlops-years} \approx 3.1 \left(\frac{N_{\text{conf}}}{100} \right) \left(\frac{L_s}{3 \text{ fm}} \right)^5 \left(\frac{L_t}{2L_s} \right) \left(\frac{0.2}{\hat{m} / m_s} \right)^3 \left(\frac{0.1 \text{ fm}}{a} \right)^7$$

Del Debbio et al. 2006:

$$\text{TFlops-years} \approx 0.03 \left(\frac{N_{\text{conf}}}{100} \right) \left(\frac{L_s}{3 \text{ fm}} \right)^5 \left(\frac{L_t}{2L_s} \right) \left(\frac{0.2}{\hat{m} / m_s} \right) \left(\frac{0.1 \text{ fm}}{a} \right)^6$$

Today: $M_\pi^{\text{latt}} \approx 250 - 300 \text{ MeV}$ ($\hat{m}_{ud}^{\text{latt}} / m_s \approx 1/6 - 1/8$) **ChPT**

Few years ago: $M_\pi^{\text{latt}} \approx 500 \text{ MeV}$ ($\hat{m}_{ud}^{\text{latt}} / m_s \approx 1/2$)



**LATTICE QCD AND
THE FIRST ROW
UNITARITY TEST**

1st row: the most stringent unitarity test

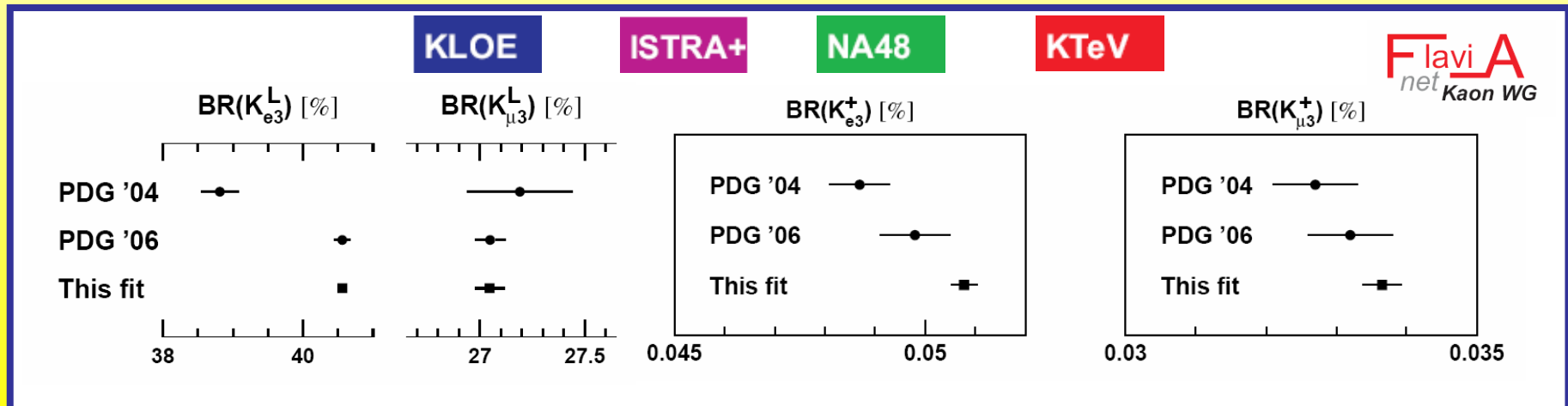
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Source:	Nuclear β -dec.	Kl2, Kl3	$b \rightarrow u$ semil.
Centr. value:	$(0.97)^2$	$(0.23)^2$	$(3.7 \cdot 10^{-3})^2$
Error:	$4 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$\sim 10^{-6}$

The PDG 2004 quoted a 2σ deviation from unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0029 \pm 0.0015$$

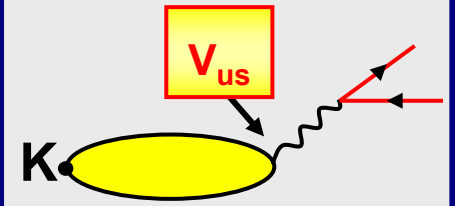
Extraordinary experimental progress in kl3 decays in the last years



V_{us}/V_{ud} from $K\mu 2/\pi\mu 2$ decays

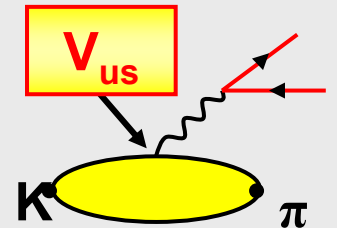
$$\frac{\Gamma(K \rightarrow \mu \bar{\nu}_\mu (\gamma))}{\Gamma(\pi \rightarrow \mu \bar{\nu}_\mu (\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2} \left(\frac{f_K}{f_\pi} \right)^2 \frac{m_K (1 - \frac{m_\mu^2}{m_K^2})}{m_\pi (1 - \frac{m_\mu^2}{m_\pi^2})} \times 0.9930(35)$$

[Marciano 04]



V_{us} from $Kl3$ decays

$$\Gamma_{K \rightarrow \pi l \nu} = C_K^2 \frac{G_F^2 m_K^5}{192 \pi^2} / S_{EW} [1 + \Delta_{SU(2)} + 2\Delta_{EM}] \times |V_{us}|^2 |f_+^{K\pi}(0)|^2$$

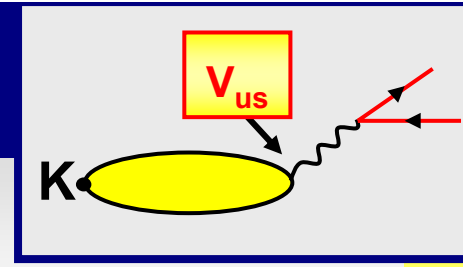


$$\frac{|V_{us}|}{|V_{ud}|} \frac{f_K}{f_\pi} = 0.27599(59)$$

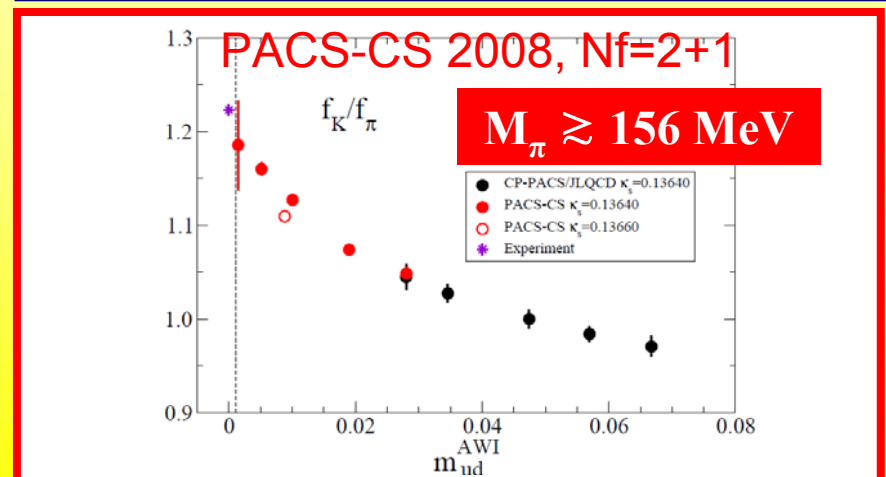
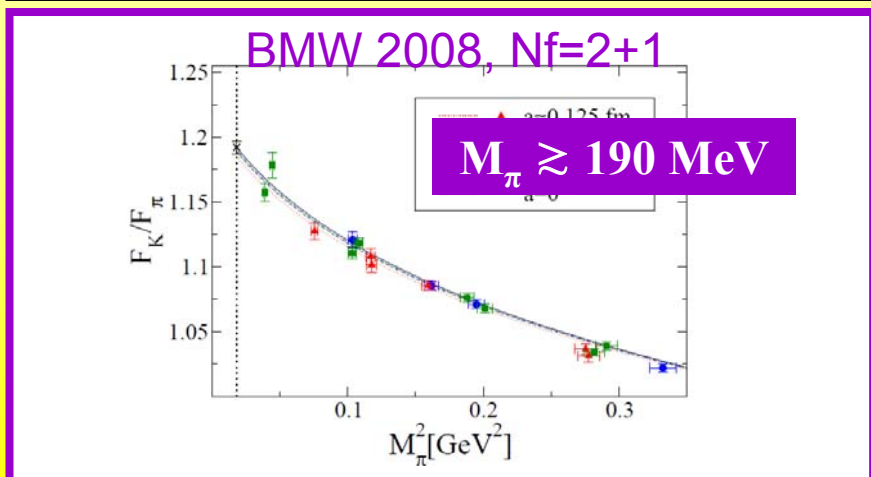
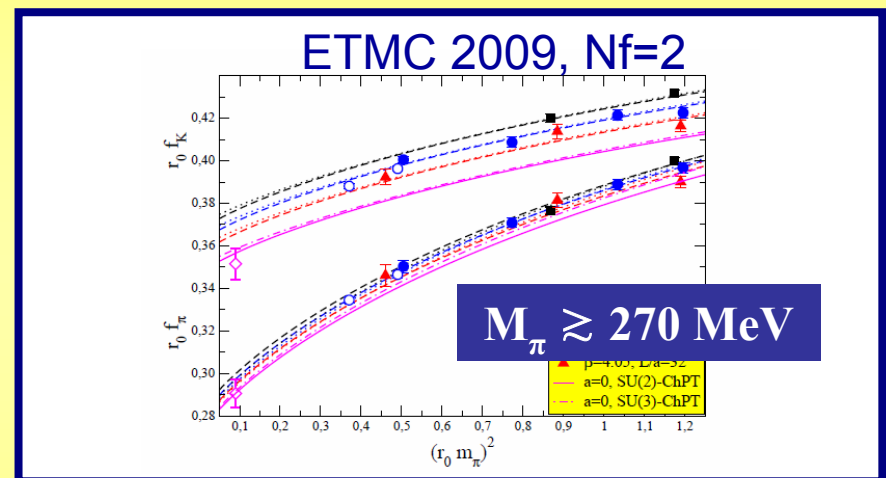
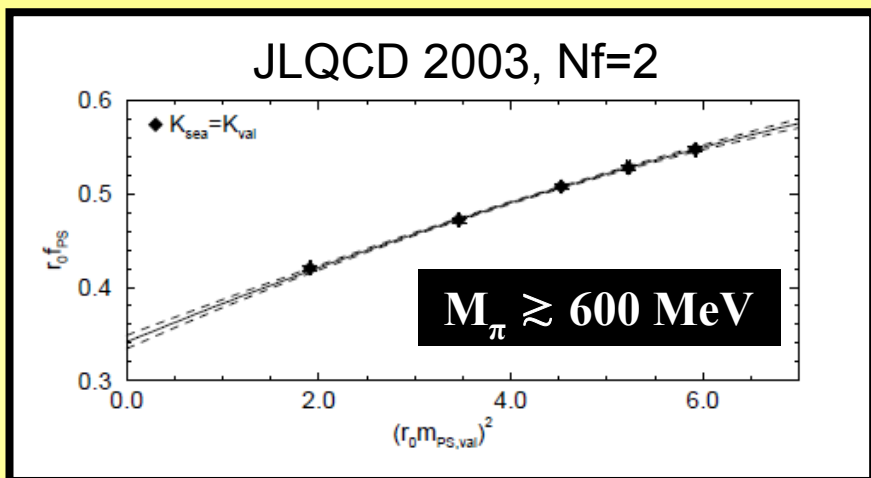
Flavi
net **A**
Kaon WG

$$|V_{us}| f_+(0) = 0.21661(47)$$

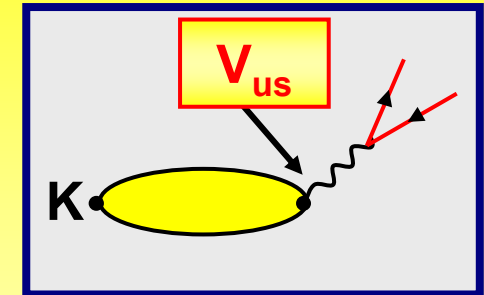
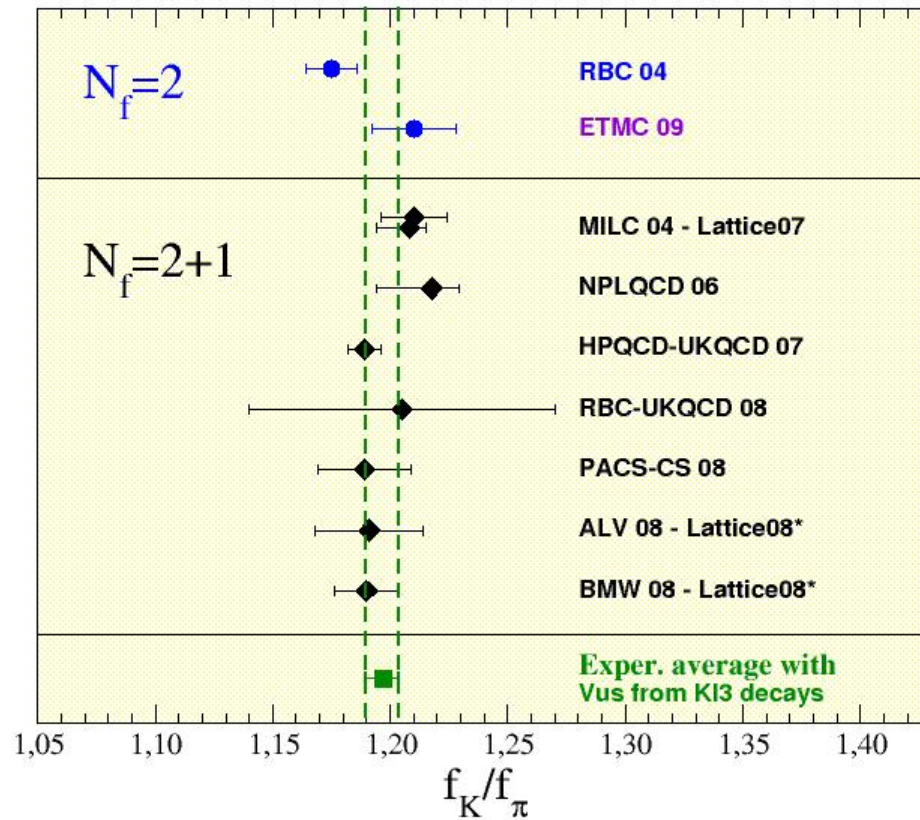
fk/f π from LATTICE QCD



- Old quenched calculations typically indicated $f_K/f_\pi - 1 \simeq 0.15$, 25% smaller than the exper. value
- Similar results were obtained by the first unquenched calculations
- A common feature of these calculations: $M_\pi \gtrsim 500$ MeV



f_K/f_π : LATTICE SUMMARY



Many new results with "light" quark masses since the last year

Good agreement with K_{l3} and CKM unitarity

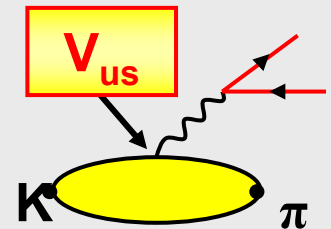
$$f_K/f_\pi = 1.194(10) \rightarrow |V_{us}| = 0.2252(20)$$

[L.Lellouch@LATT'08]

combined with $|V_{ud}| = 0.97425(22)$ from nuclear β decay

V_{us} from K13 decays

$$\Gamma_{K \rightarrow \pi l \nu} = C_K^2 \frac{G_F^2 m_K^5}{192 \pi^2} / S_{EW} [1 + \Delta_{SU(2)} + 2\Delta_{EM}] \times |V_{us}|^2 |f_+^{K\pi}(0)|^2$$



Ademollo-Gatto: $f_+(0) = 1 - O(m_s - m_u)^2 \leftarrow O(1\%)$. But represents the largest theoret. uncertainty

SU(3)-ChPT

$$f_+(0) = 1 + f_2 + f_4 + O(p^8)$$

Vector Current Conservation

$f_2 = -0.023$
Independent of L_i
(Ademollo-Gatto)

THE LARGEST UNCERTAINTY

Old standard estimate:
Leutwyler, Roos (1984)
(QUARK MODEL)
 $f_4 = -0.016 \pm 0.008$

Analytical calculations of f_4 are model dependent

$$f_4 = \Delta_{\text{loops}}(\mu) - \frac{8}{F_\pi^4} [C_{12}(\mu) + C_{34}(\mu)] (M_K^2 - M_\pi^2)^2$$

Post, Schilcher, '01
Bijnens, Talavera, '03

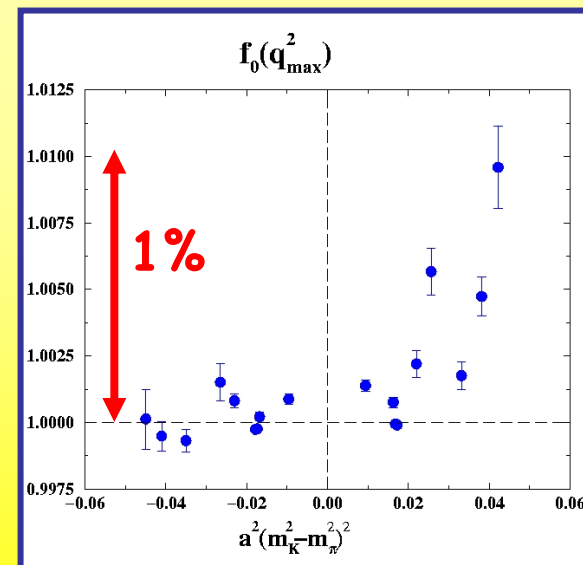
Bijnens, Talavera,	$f_4^{\text{LOC}} = -0.016 \pm 0.008$	[Quark model, Leutwyler, Ross]
Jamin, Oller, Pich,	$f_4^{\text{LOC}} = -0.018 \pm 0.009$	[Dispersive analysis]
Cirigliano et al.,	$f_4^{\text{LOC}} = -0.002 \pm 0.008$	[$1/N_c$ +low resonance satur.]

Lattice QCD

THE **O(1%)** PRECISION CAN BE REACHED

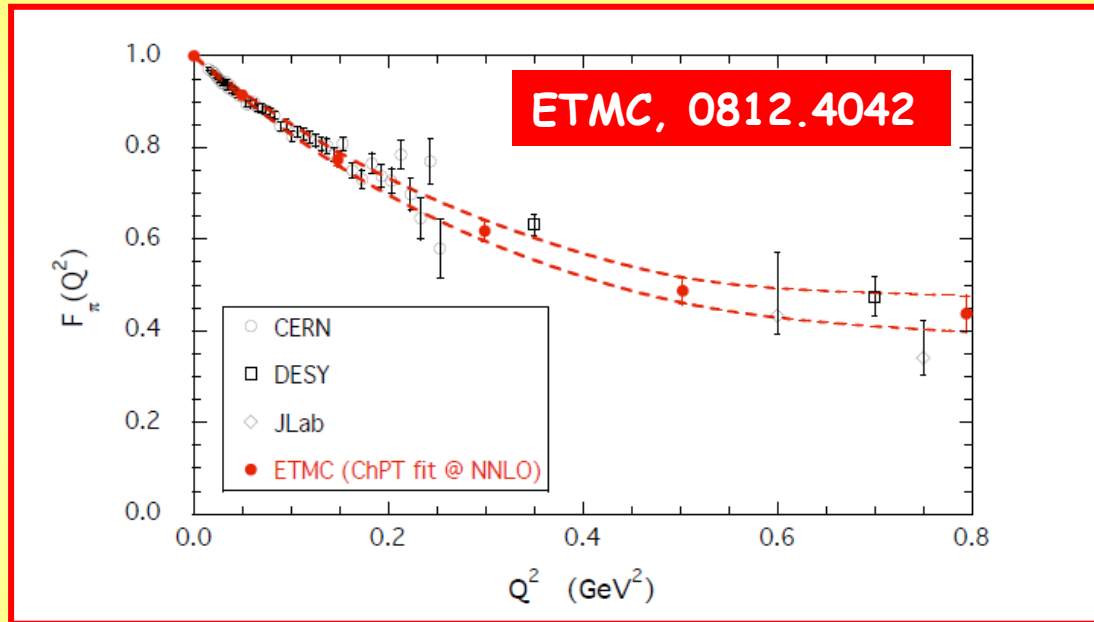
D. Becirevic, G. Isidori, V.L., G. Martinelli, F. Mescia,
S. Simula, C. Tarantino, G. Villadoro. [NPB 705, 339, 2005]

The basic ingredient is a **double ratio** of correlation functions [FNAL for $B \rightarrow D, D^*$]



The pion electromagnetic form factor

An important test for Lattice QCD calculations of $Kl3$ form factors: precise experimental data, no CKM factor



The European Twisted Mass Collaboration

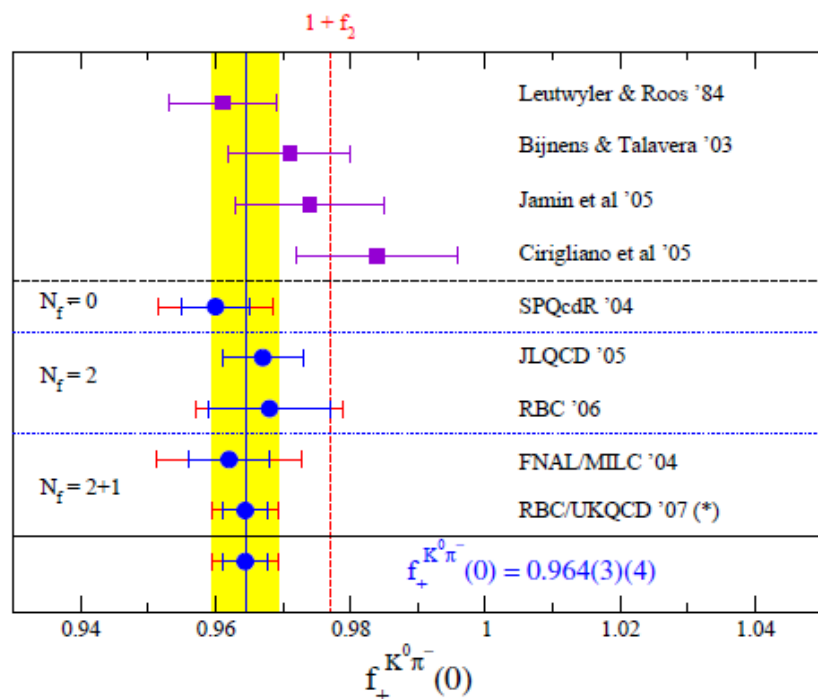
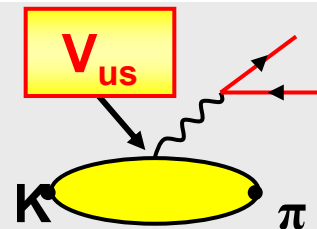


Advanced techniques:

- All-to-all stochastic propagators → very good statistical accuracy

- Twisted boundary cond. → continuously varying lattice momenta: $\vec{p} = \vec{\theta} + \frac{2\pi}{aL} \vec{n}$

$f_+(0)$: LATTICE SUMMARY



- Analytical (model dependent) results slightly higher than Lattice QCD
- Good agreement between lattice calculations ($N_f=0, 2, 2+1$)

[L.Lellouch @ LATT'08]

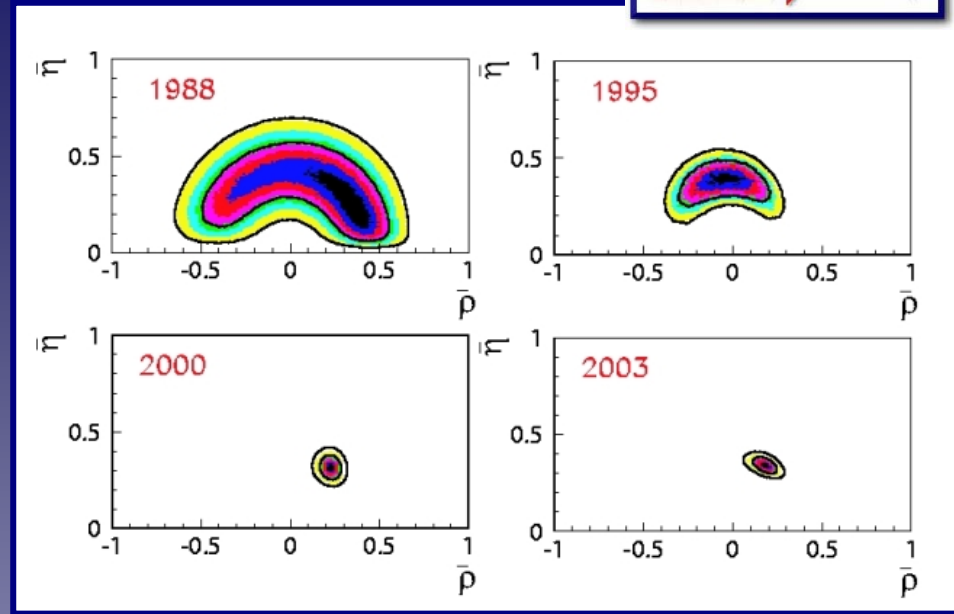
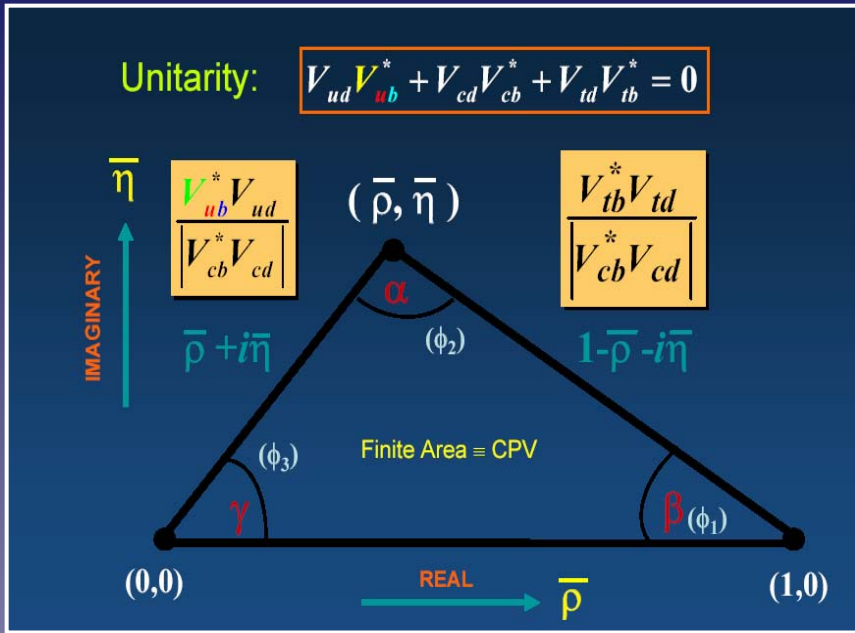
$$f_+(0) = 0.964(5) \rightarrow |V_{us}|_{kl3} = 0.2247(13)$$

$$|V_{us}|_{kl2} = 0.2252(20)$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0003 \pm 0.0007$$

LATTICE QCD AND THE
UNITARITY TRIANGLE
ANALYSIS

15 years of Unitarity Triangle Analysis



Lattice results are available since many years
 Remarkable predictions of (quenched) lattice QCD:

Ciuchini et al., 1995:
 $\text{Sin}2\beta_{\text{UTA}} = 0.65 \pm 0.12$

Direct measurement:
 $\text{Sin}2\beta_{\text{J}/\psi \text{ K}0} = 0.668 \pm 0.026$

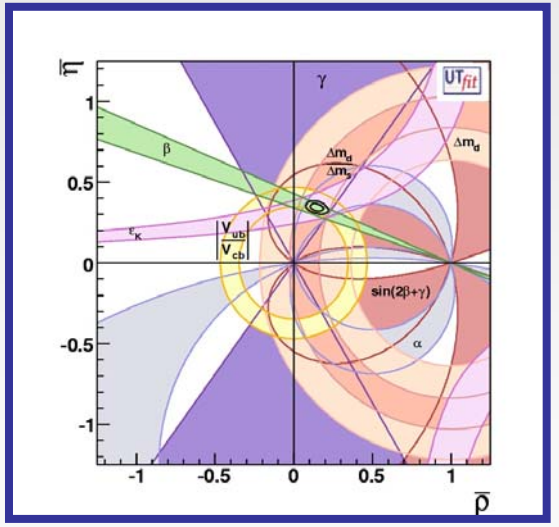
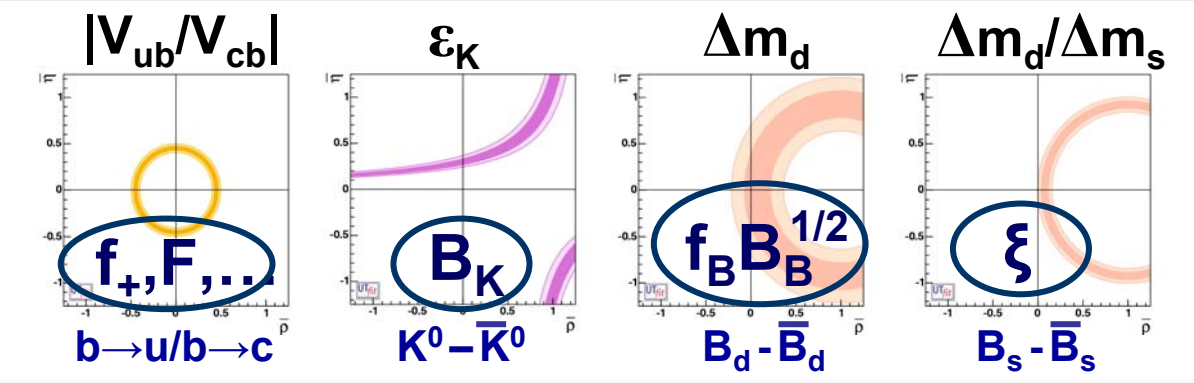
Ciuchini et al., 2000:
 $\Delta m_s = (16.3 \pm 3.4) \text{ ps}^{-1}$

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

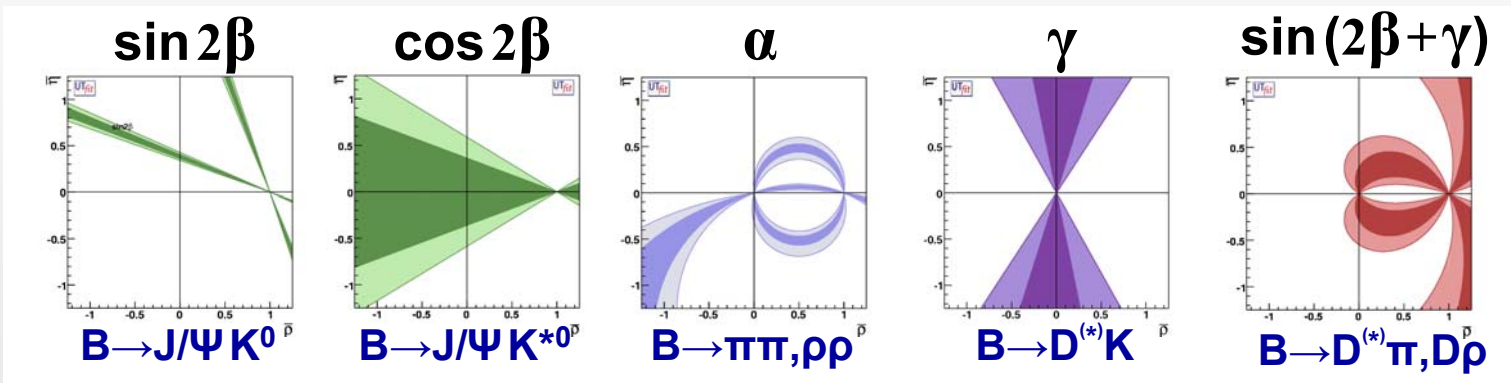
THE UT FIT TODAY



UT-LATTICE



UT-ANGLES



$K^0 - \bar{K}^0$ mixing: B_K

$$\langle \bar{K}^0 | Q(\mu) | K^0 \rangle = \frac{8}{3} f_K^2 m_K^2 B_K(\mu)$$

$$\hat{B}_K = 0.86 \pm 0.05 \pm 0.14$$

L. Lellouch @ Latt'00

Quench.
error

$$\hat{B}_K = 0.79 \pm 0.04 \pm 0.08$$

C. Dawson @ Latt'05

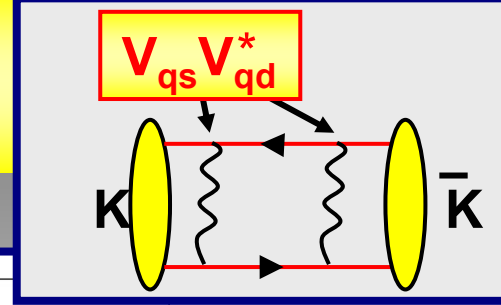
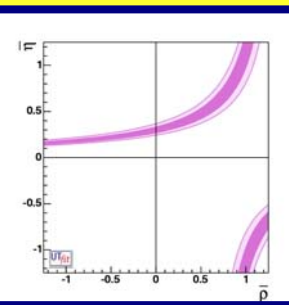
$$\hat{B}_K = 0.723 \pm 0.037$$

L. Lellouch @ Latt'08

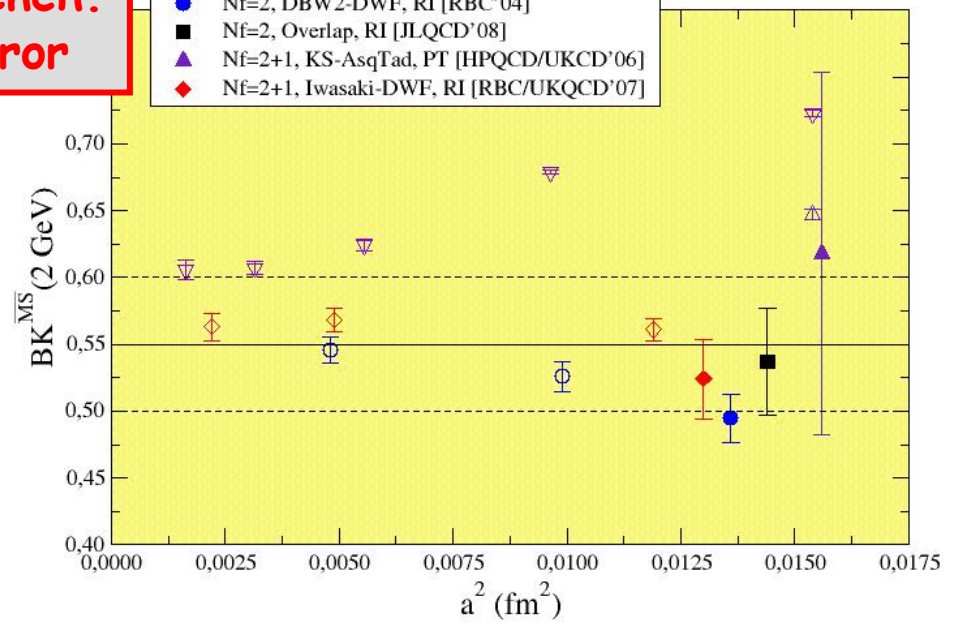
$$\hat{B}_K = 0.750 \pm 0.070$$

VL, C. Tarantino for UTfit

NEEDED: multiplicative and non-perturb. renorm. + contin. extrapol.



- Nf=0, DBW2-DWF, RI [RBC'05]
- ◇ Nf=0, Iwasaki-DWF, SF [CP-PACS'08]
- △ Nf=0, KS-AsqTad, PT [HPQCD/UKQCD'06]
- Nf=2, DBW2-DWF, RI [RBC'04]
- Nf=2, Overlap, RI [JLQCD'08]
- ▲ Nf=2+1, KS-AsqTad, PT [HPQCD/UKQCD'06]
- ◆ Nf=2+1, Iwasaki-DWF, RI [RBC/UKQCD'07]



LQCD, Gavela et al., 1987:

$$\hat{B}_K = 0.90 \pm 0.20$$

QCD SR, Pich, De Rafael, 1985:

$$\hat{B}_K = 0.33 \pm 0.09$$

$K^0 - \bar{K}^0$ mixing: B_K

$$\langle \bar{K}^0 | Q(\mu) | K^0 \rangle = \frac{8}{3} f_K^2 m_K^2 B_K(\mu)$$

$$\hat{B}_K = 0.86 \pm 0.05 \pm 0.14$$

L. Lellouch @ Latt'00

Quench.
error

$$\hat{B}_K = 0.79 \pm 0.04 \pm 0.08$$

C. Dawson @ Latt'05

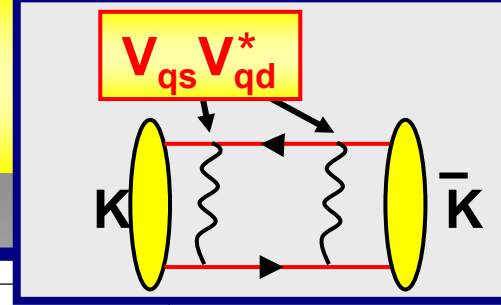
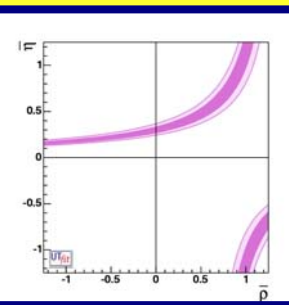
$$\hat{B}_K = 0.723 \pm 0.037$$

L. Lellouch @ Latt'08

$$\hat{B}_K = 0.750 \pm 0.070$$

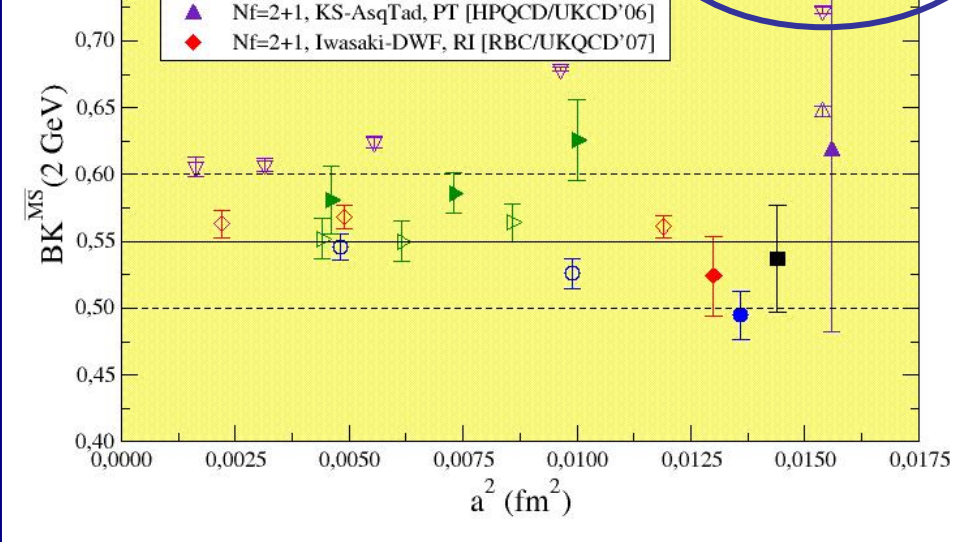
VL, C. Tarantino for UTfit

NEEDED: multiplicative and non-perturb. renorm. + contin. extrapol.



- Nf=0, DBW2-DWF, RI [RBC'05]
- ◇ Nf=0, Iwasaki-DWF, SF [CP-PACS'08]
- △ Nf=0, KS-AsqTad, PT [HPQCD/UKQCD'06]
- ▽ Nf=0, Wilson-TM/OS, SF [ALPHA'09]
- Nf=2, DBW2-DWF, RI [RBC'04]
- Nf=2, Overlap, RI [JLQCD'08]
- ▼ Nf=2, tSym-TM/OS, RI [ETMC'09 *]
- ▲ Nf=2+1, KS-AsqTad, PT [HPQCD/UKCD'06]
- ◆ Nf=2+1, Iwasaki-DWF, RI [RBC/UKQCD'07]

With new preliminary ETMC data



LQCD, Gavela et al., 1987:

$$\hat{B}_K = 0.90 \pm 0.20$$

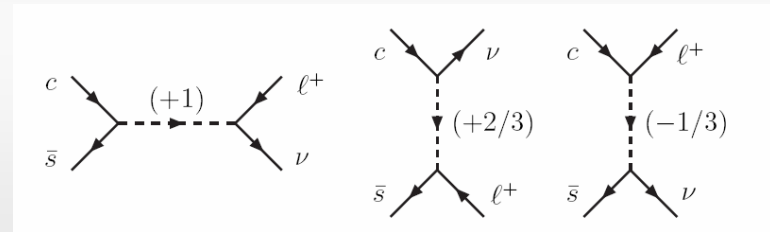
QCD SR, Pich, De Rafael, 1985:

$$\hat{B}_K = 0.33 \pm 0.09$$

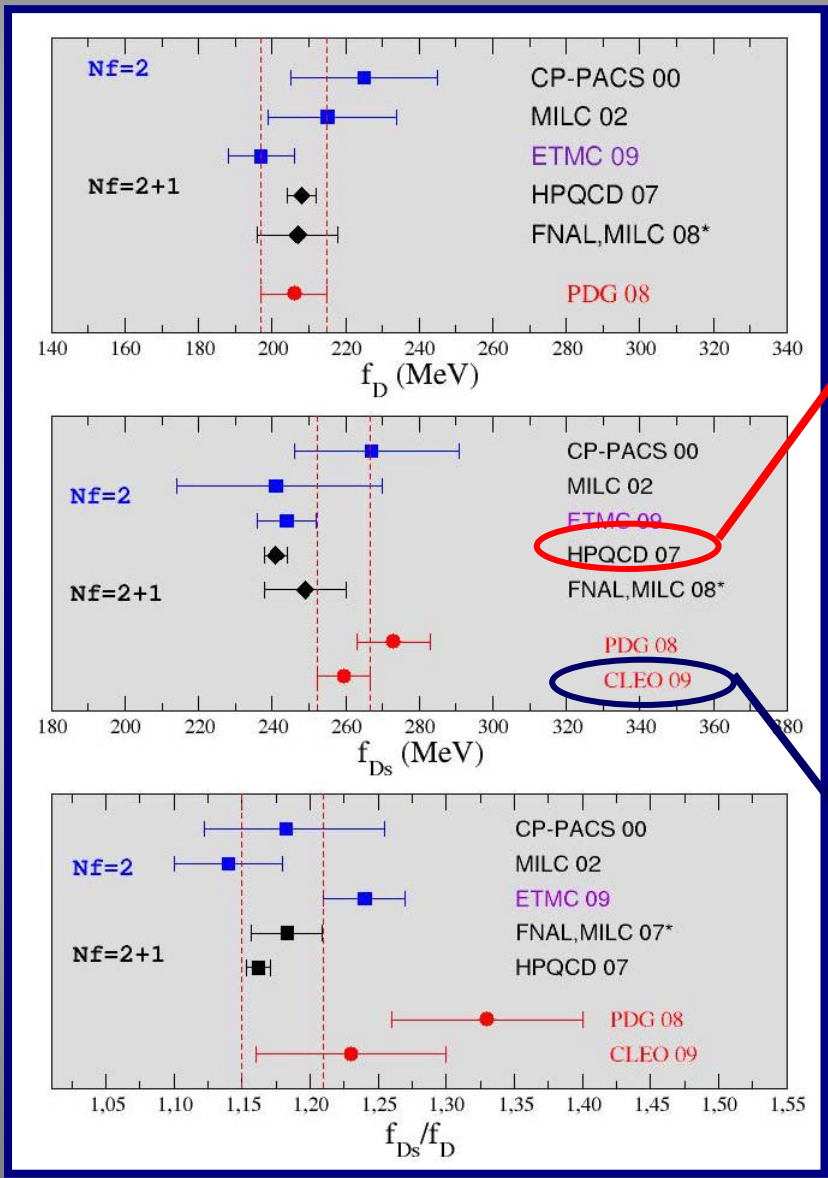
D-mesons decay constants: f_D, f_{D_s}

A lattice result by **HPQCD**, which claims a 1.2% precision on f_{D_s} , shows a **discrepancy of about 3.5σ** with the PDG'08 average.

B. Dobrescu, A. Kronfeld, 0803.0512:
"Evidence for nonstandard leptonic decays of D_s mesons"

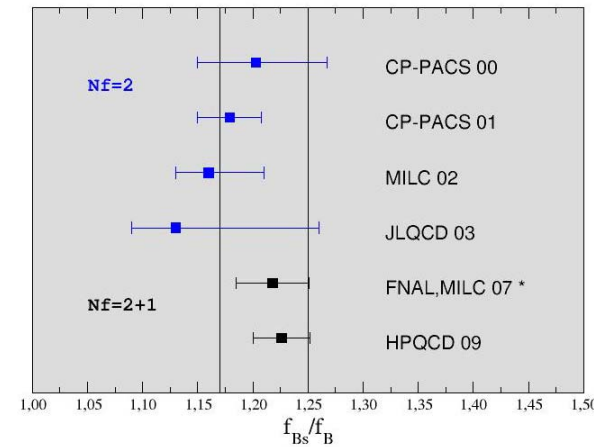
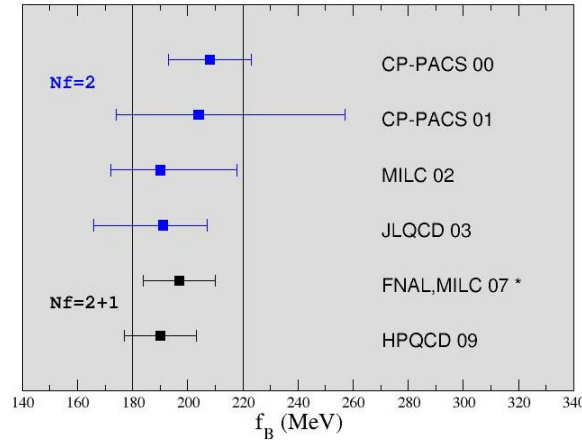
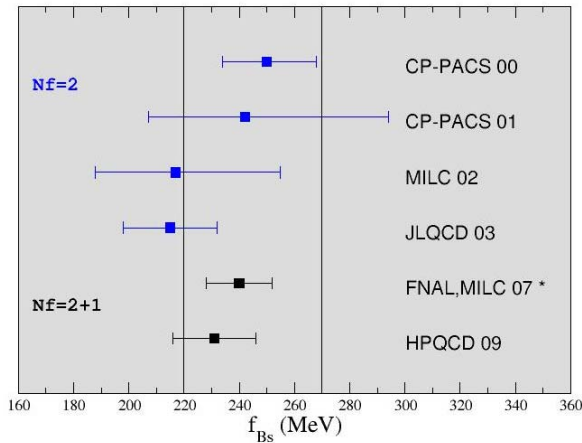


The **tension** between lattice QCD and experiments **disappears with the new CLEO results**



B-mesons decay constants: f_B, f_{B_s}

Lattice inputs for $\Delta m_{d/s}$ and $B \rightarrow \tau \nu$



Averages used in the UT fit

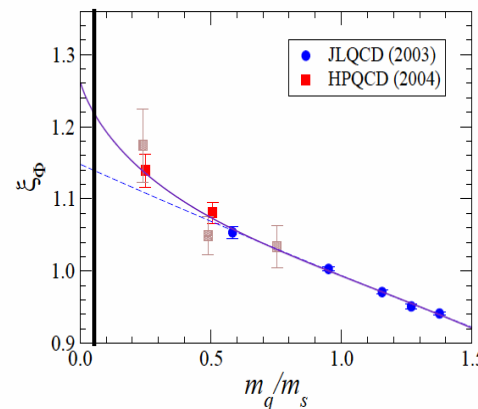
[VL, C.Tarantino 0807.4605]

$$f_{B_s} = 245 \pm 25 \text{ MeV}$$

$$f_B = 200 \pm 20 \text{ MeV}$$

$$f_{B_s}/f_B = 1.21 \pm 0.04$$

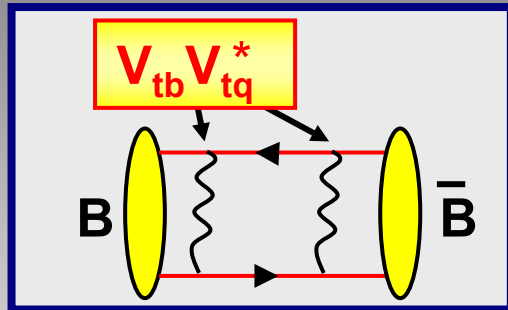
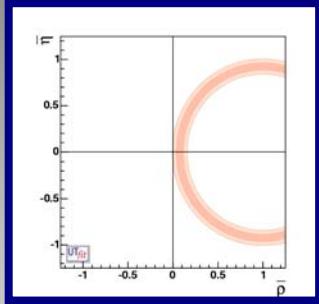
Only 2 recent calculations (with staggered fermions and the b-quark with FNAL or NRQCD)



Chiral logs effects

Light m_q ($< m_s/2$) important for f_B

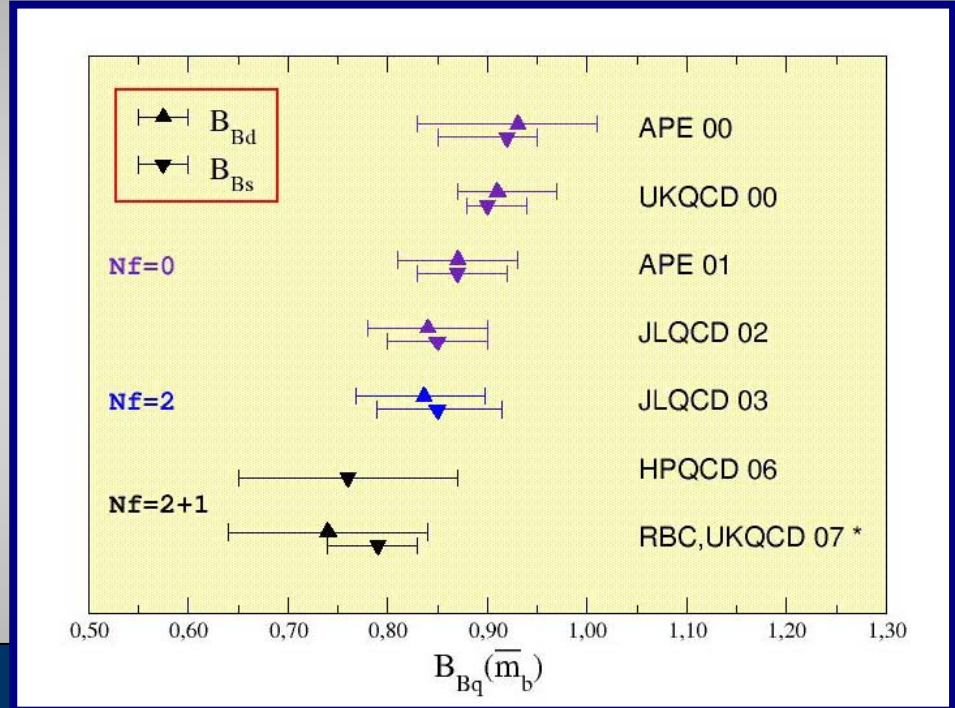
B- \bar{B} mixing: B_{B_d} and B_{B_s}



$$\langle \bar{B} | Q(\mu) | B \rangle = \frac{8}{3} m_B^2 f_B^2 B_B(\mu)$$

-Small SU(3) breaking effects: $B_{B_d} \approx B_{B_s}$

-Small quenching effects: consistent $N_f=0$, $N_f=2$ and $N_f=2+1$ results



Averages used in the UT fit

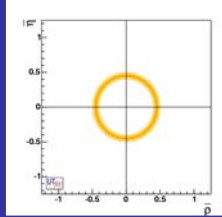
$$f_{B_s} \sqrt{\hat{B}_{B_s}} = 270 \pm 30 \text{ MeV}$$

$$\xi = 1.21 \pm 0.04$$

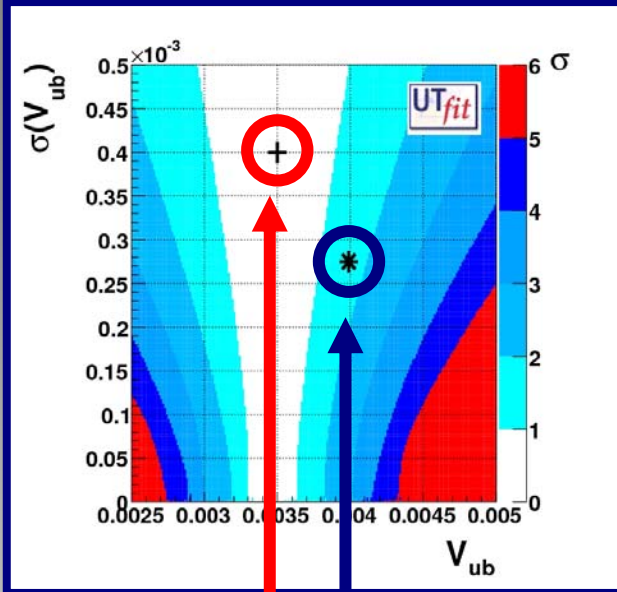
$$B_{B_d}(\bar{m}_b) = B_{B_s}(\bar{m}_b) =$$

$$0.80 \pm 0.08$$

V_{ub} from $B \rightarrow \pi l \nu$ decays



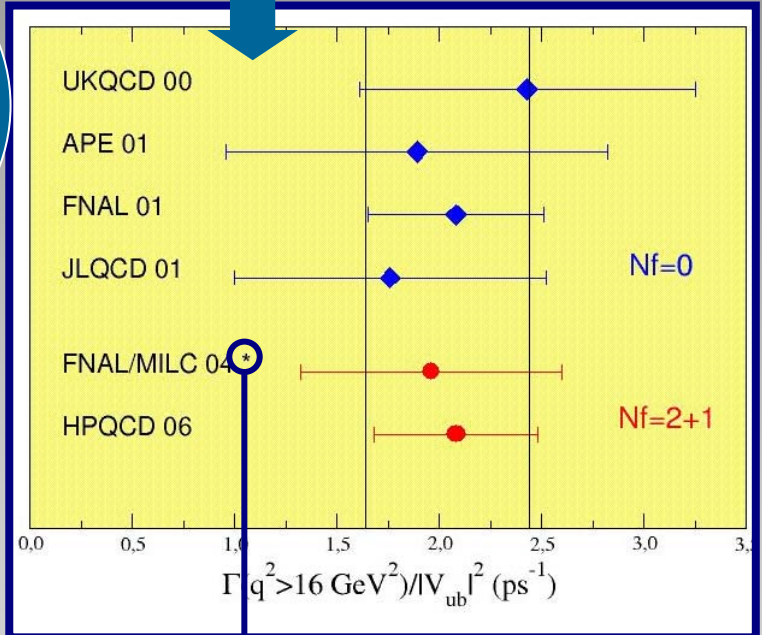
The tension between **inclusive** V_{ub} and the **UT fit** is disappearing



MORE
"MODERN"
LATTICE
CALCULATIONS
REQUIRED

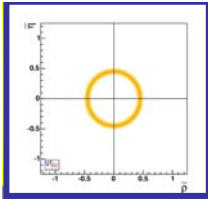
EXCLUSIVE: $V_{ub}^{excl.} = (3.5 \pm 0.4) 10^{-3}$
Form factors from LQCD and QCDSR

INCLUSIVE: $V_{ub}^{incl.} = (4.00 \pm 0.15 \pm 0.40) 10^{-3}$
Model dependent in the threshold region
(BLNP, DGE, BLL, ...)



Updated in 0811.3640:
 $|V_{ub}|_{excl.} = (3.38 \pm 0.36) 10^{-3}$
from a combination of
lattice and BaBar data

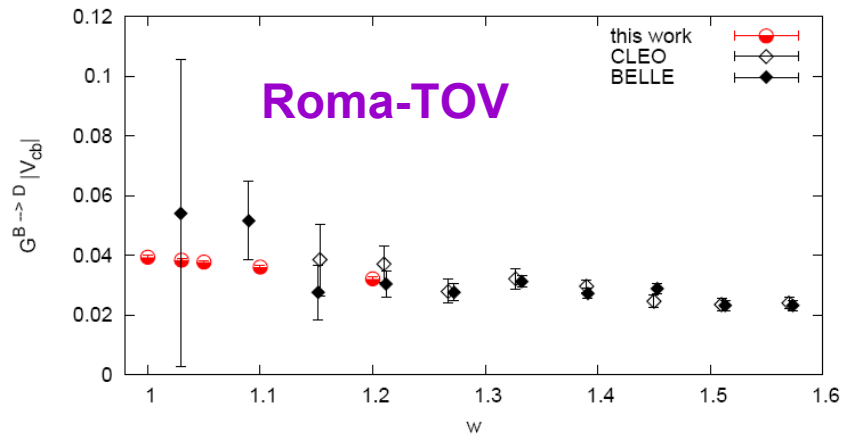
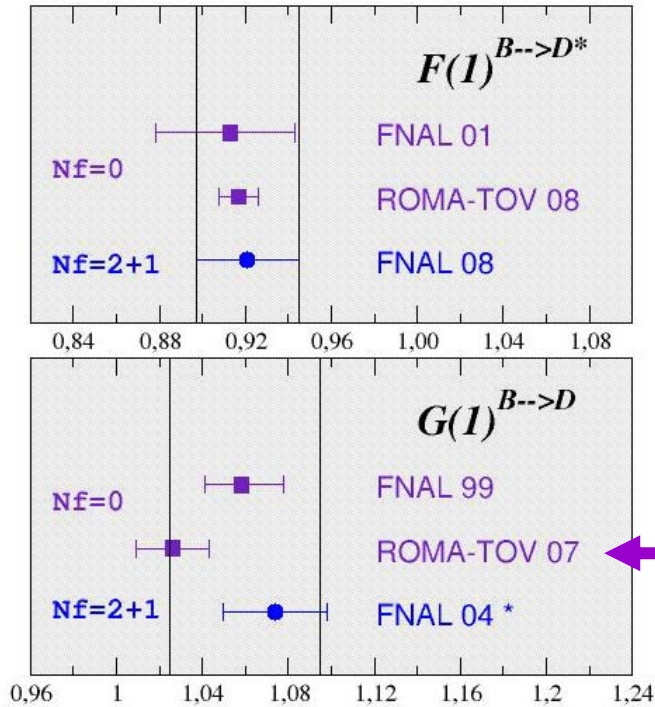
Vcb from $B \rightarrow D/D^* l \nu$ decays



TWO DIFFERENT APPROACHES:

- "double ratios" (FNAL)
- "step scaling" (TOV)

Remarkable agreement



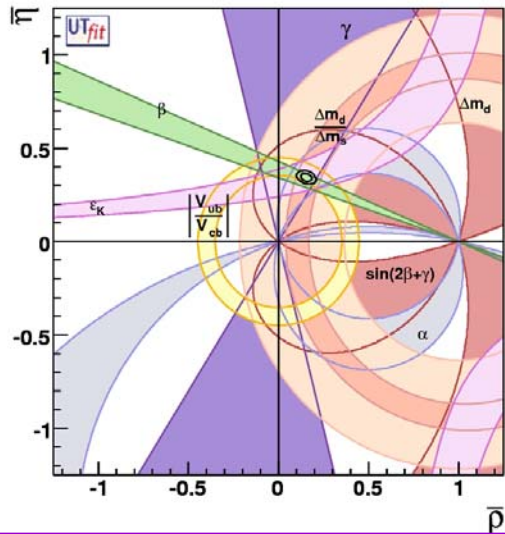
$F(1) = 0.924 \pm 0.022$ **2.4%**

$G(1) = 1.060 \pm 0.035$ **3.3%**

[VL, C.Tarantino for UTfit]

UTfit: THE STANDARD MODEL ANALYSIS

THE FULL UTA

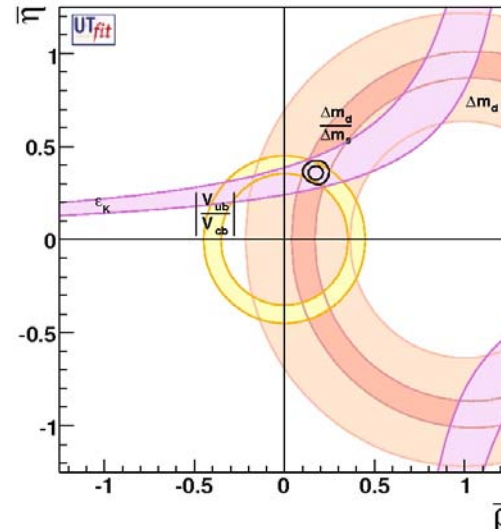


$$\bar{\rho} = 0.155 \pm 0.022 \quad 14\%$$

$$\bar{\eta} = 0.342 \pm 0.014 \quad 4.1\%$$

$$A = 0.809 \pm 0.013 \quad 1.6\%$$

$$\lambda = 0.2259 \pm 0.0015 \quad 0.7\%$$



UT-LATTICE

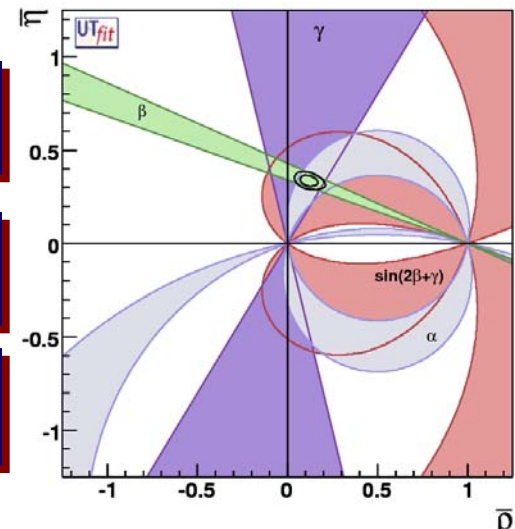
$$\bar{\rho} = 0.175 \pm 0.027$$

$$\bar{\eta} = 0.360 \pm 0.023$$

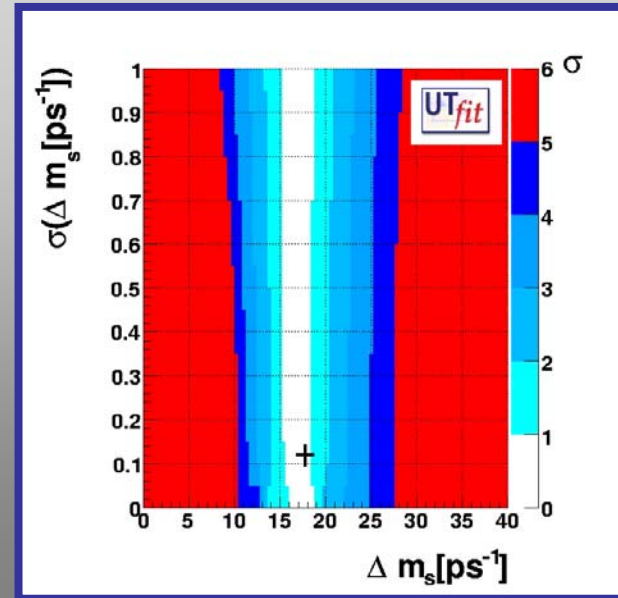
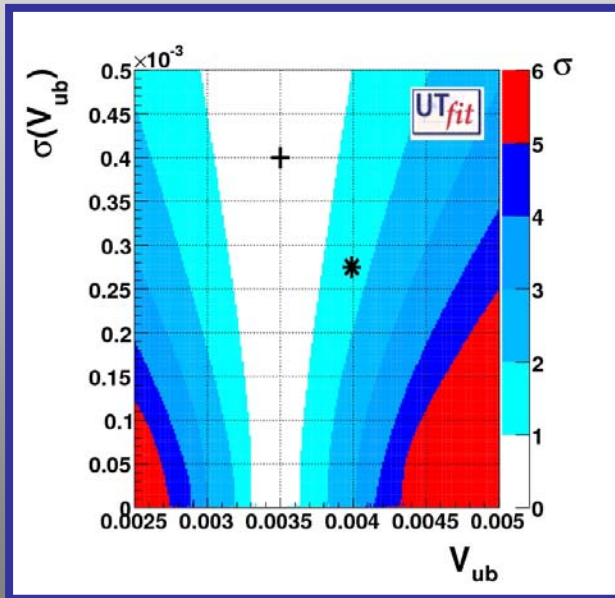
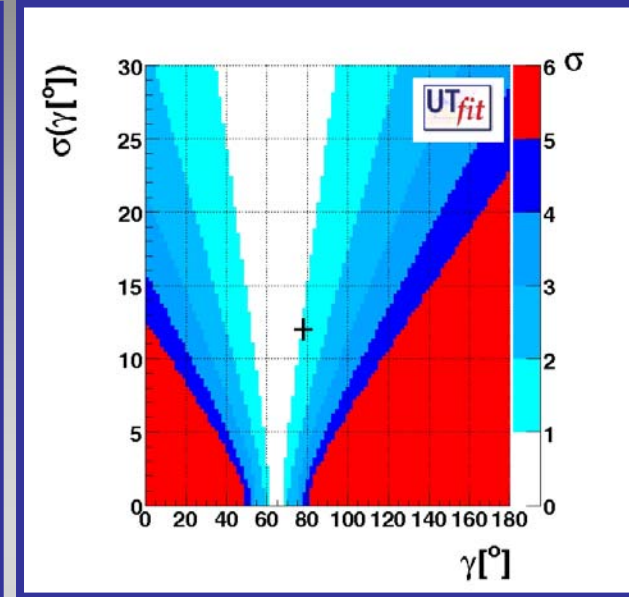
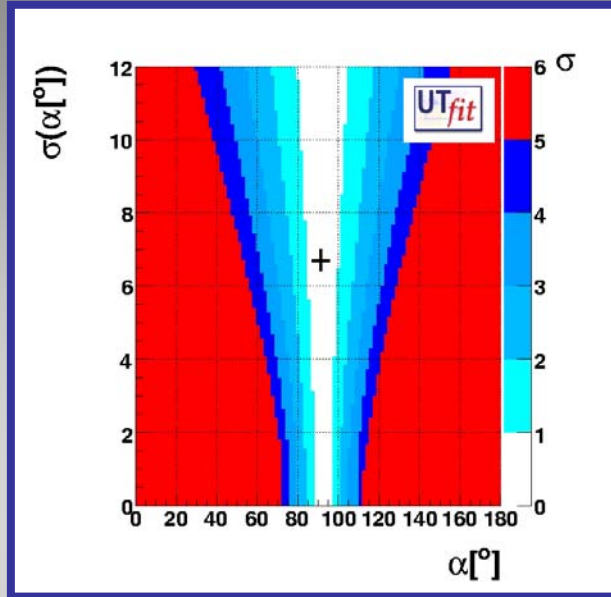
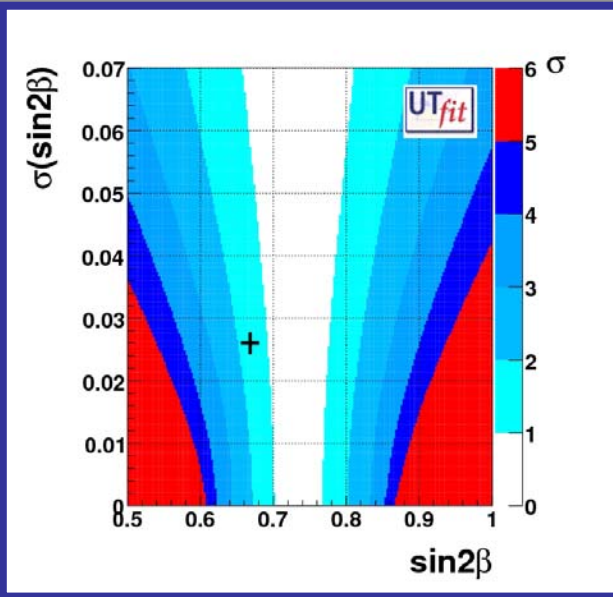
UT-ANGLES

$$\bar{\rho} = 0.120 \pm 0.034$$

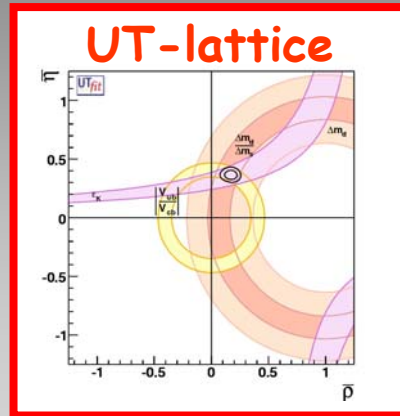
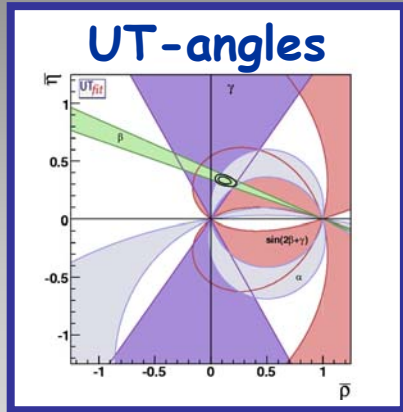
$$\bar{\eta} = 0.335 \pm 0.020$$



UTfit in the SM: the compatibility plots



UT FIT OF LATTICE PARAMETERS



Assuming the validity of the **Standard Model** one can perform a fit of the hadronic parameters:

1.4%! from Δm_s

	B_K	$f_{B_s} \sqrt{B_{B_s}}$ (MeV)	ξ
UTA	0.78 ± 0.07	265.6 ± 3.6	1.27 ± 0.05
Lattice	0.75 ± 0.07	270 ± 30	1.21 ± 0.04

Very good agreement: a success for the SM

Lattice QCD is almost "irrelevant" for the SM analysis

NEW PHYSICS: THE MODEL DEPENDENT

New Physics effects are described by the low-energy effective Hamiltonian

$$\langle M | H_{\text{eff}}^{\text{NP}} | \bar{M} \rangle = \sum_i C_i(\mu) \underbrace{\langle M | Q_i(\mu) | \bar{M} \rangle}_{\text{LATTICE QCD}}$$

NEW PHYSICS SCALE

LATTICE QCD

...AND MODEL INDEPENDENT ANALYSIS

New Physics in $\Delta F = 2$ amplitudes is parameterized in a general form

$$C_{B_d} e^{2i\varphi_{B_d}} = \frac{\langle B_d^0 | H_{\text{eff}}^{\text{full}} | \bar{B}_d^0 \rangle}{\langle B_d^0 | H_{\text{eff}}^{\text{SM}} | \bar{B}_d^0 \rangle}$$

6 additional free parameters

$$C_{B_d}, \varphi_{B_d}, C_{B_s}, \varphi_{B_s}, C_{\varepsilon K}, C_{\Delta m K}$$

E.g.: $(\Delta m_d)^{\text{exp}} = C_{B_d} (\Delta m_d)^{\text{SM}}$, $\sin 2\beta^{\text{exp}} = \sin 2(\beta^{\text{SM}} + \varphi_{B_d})$

In the Standard Model: $C_{xx} = 1$, $\varphi_{xx} = 0$

MATRIX ELEMENTS FOR $K-\bar{K}$ AND $B-\bar{B}$ MIXING BEYOND THE STANDARD MODEL

	B_1^{sd}	B_2^{sd}	B_3^{sd}	B_4^{sd}	B_5^{sd}
APE 99	0.68(21)	0.67(7)	0.95(15)	1.00(9)	0.66(11)
Babich et al 06	0.56(6)	0.87(8)	1.41(16)	0.94(6)	0.62(8)
CP-PACS 06 *	0.52(4)	0.54(2)	0.71(2)	0.70(1)	0.62(1)

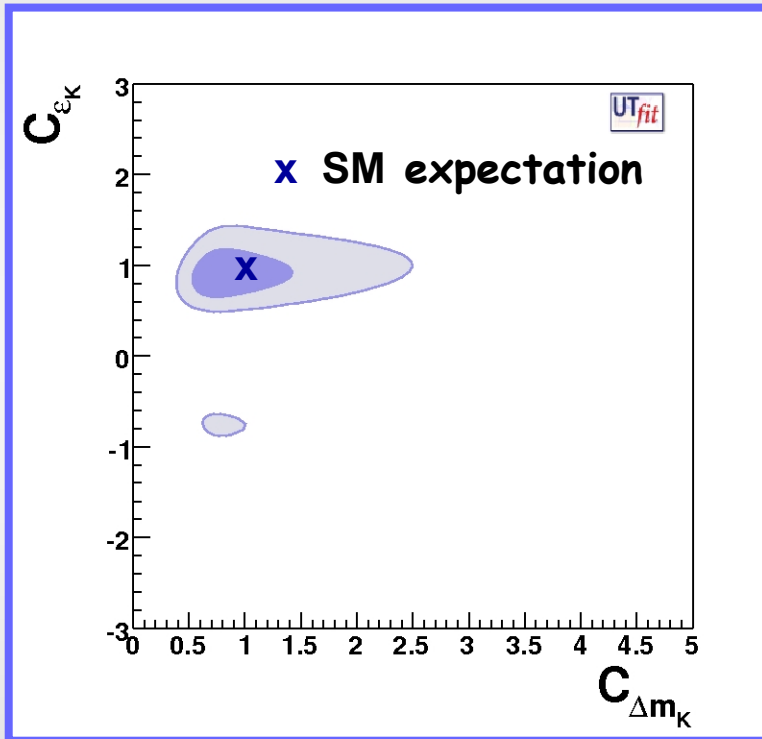
	R_1^{sd}	R_2^{sd}	R_3^{sd}	R_4^{sd}	R_5^{sd}
APE 99	1	-7(2)	1.9(6)	12(3)	2.6(9)
Babich et al. 06	1	-16(3)	5.2(9)	21(3)	4.6(9)
CP-PACS 06 *	1	-19(1)	5.0(3)	30(3)	8.8(7)

	B_1^{bs}	B_2^{bs}	B_3^{bs}	B_4^{bs}	B_5^{bs}
APE 01	0.84(5)	0.84(4)	0.91(9)	1.15(6)	1.74(7)
JLQCD 02	0.86(5)	0.86(5)	—	—	—
HPQCD 06	0.76(11)	0.84(13)	0.90(14)	—	—

The full operator basis only in the quenched approximation
 For $K-\bar{K}$ mixing results quite in disagreement

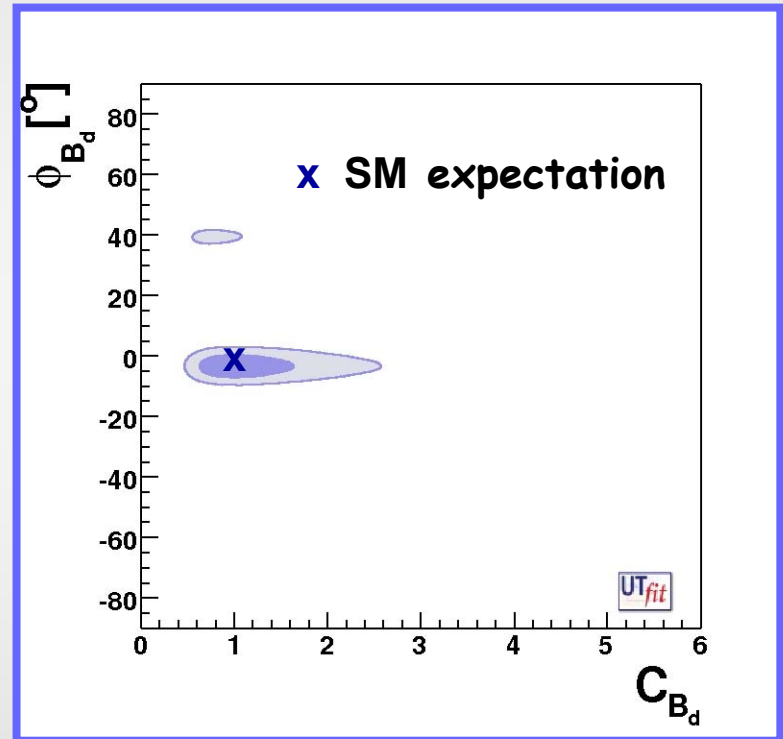
THE MODEL INDEPENDENT ANALYSIS

K- \bar{K} mixing



$$C_{\epsilon_K} = 0.91 \pm 0.13$$

B_d - \bar{B}_d mixing



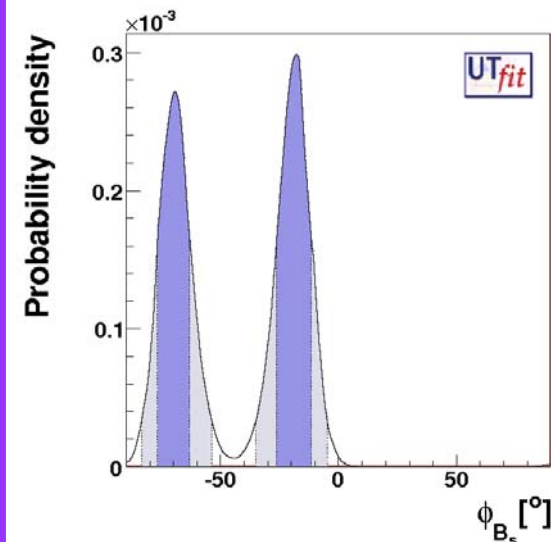
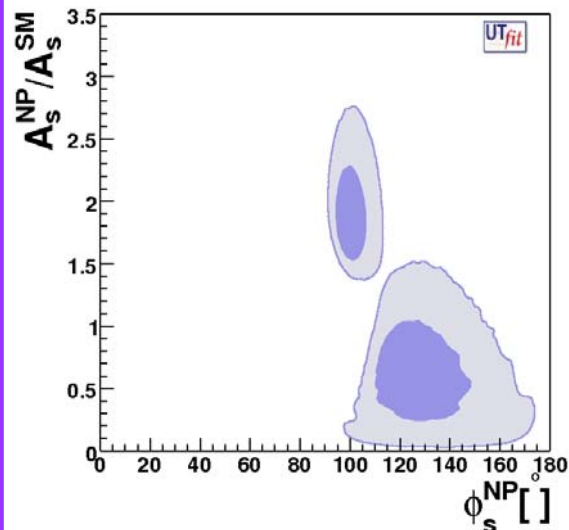
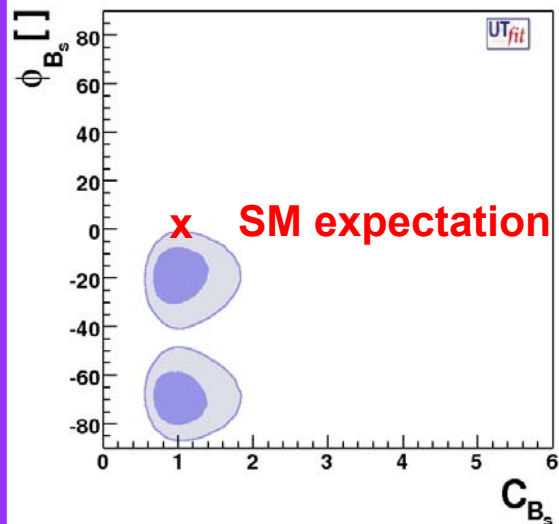
$$C_{B_d} = 0.90 \pm 0.23$$

$$\phi_{B_d} = (-2.7 \pm 1.9)^\circ$$

HINT OF NEW PHYSICS IN B_s MIXING

(update from UTfit Coll., 0803.0659)

The CP asymmetry in $B_s \rightarrow J/\Psi \phi$ measured by



$$C_{B_s} = 0.99 \pm 0.23$$

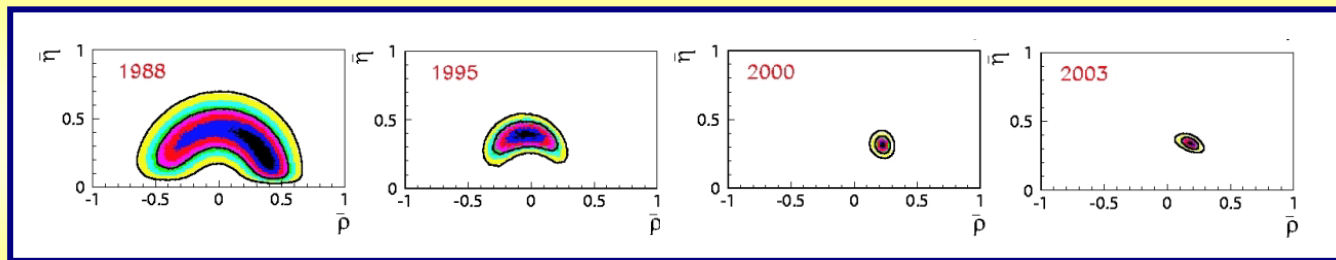
$$\phi_{B_s} = (-18.4 \pm 7.6)^\circ \cup (-69.7 \pm 6.6)^\circ$$

The p.d.f. is asymmetric:

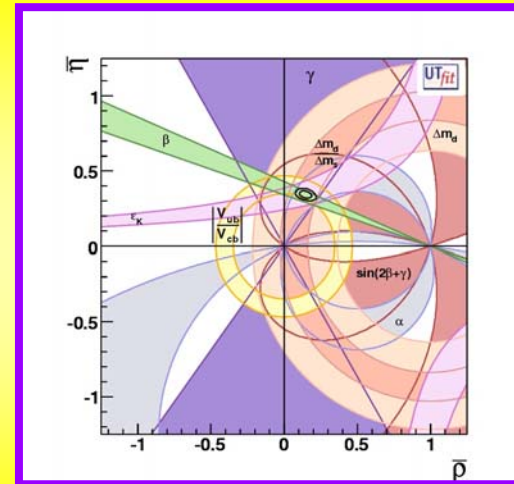
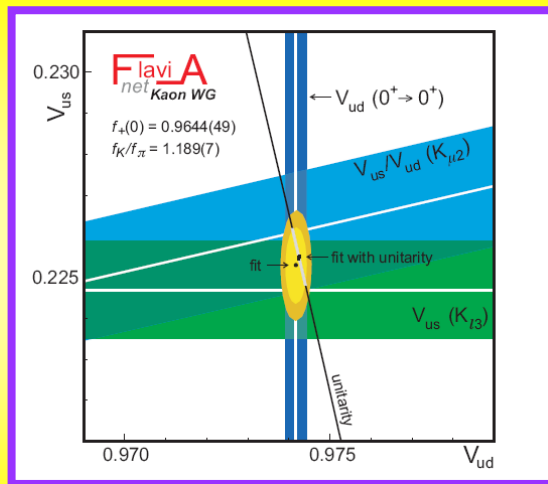
$$\phi_{B_s} = (-16.6 + 5.8 - 9.3)^\circ \cup \dots$$

**THE STANDARD MODEL
IS AT ~ 2.9 SIGMA**

The past



the present



and the future

