Lattice QCD, Flavor Physics and the Unitarity Triangle Analysis

UNIVERSITÀ DEGLI STUDI ROMA TRE

Vittorio Lubicz

OUTLINE

1. Impact of lattice calculations in the UT Fits
2. Review of lattice results
3. Determination of lattice hadronic parameters from UT Fits
4. Vus and Kl3 decays from LQCD

Heavy Quarks and Leptons

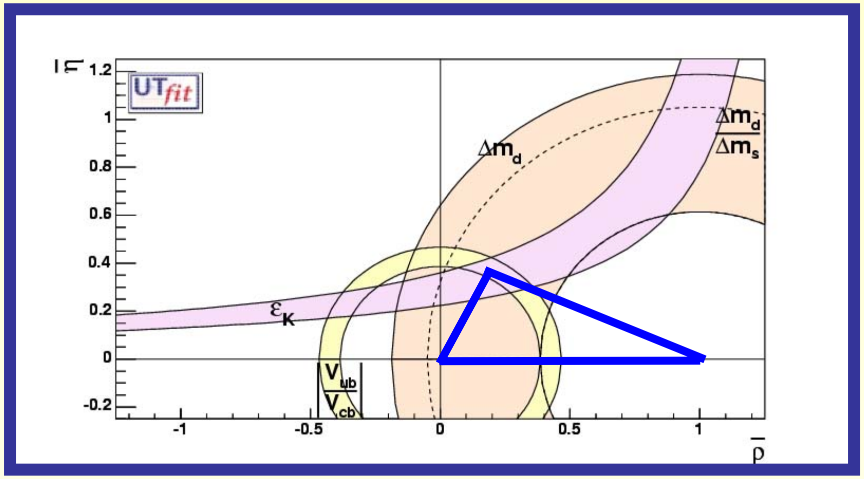
Munich, 16-20 October, 2006

THE "UT-LATTICE" ANALYSIS:

UTA IN THE PRE-B FACTORIES ERA:

CP-conserving sizes + ε_K

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



Hadronic matrix elements from LATTICE QCD

$(b\to u)/(b\to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$f_+, F(1), \dots$
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f_{B_d}^2 B_{B_d}$
$\Delta m_d / \Delta m_s$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
ε_K	$\bar{\eta}[(1-\bar{\rho}) + P]$	B_K

4 CONSTRAINTS

2 PARAMETERS

Already before the starting of the B factories

3 IMPORTANT RESULTS FOR FLAVOUR PHYSICS

1) Confirmation of the CKM origin of $\not{CP}$ in K-$\bar{K}$ mixing

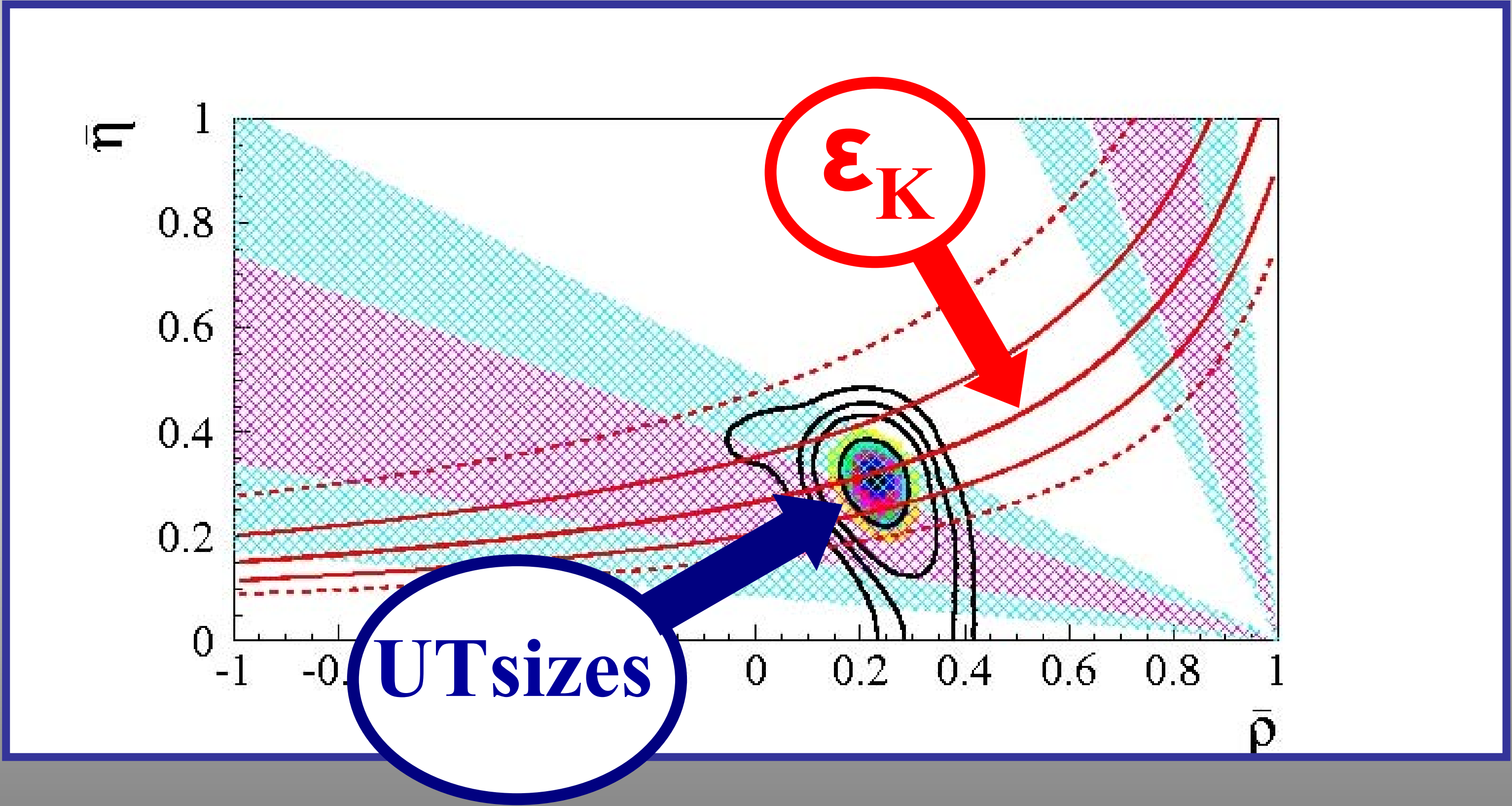
2) Prediction of $\sin 2\beta$

3) Prediction of Δm_s

A great success of (quenched) Lattice QCD calculations !!

1) INDIRECT EVIDENCE OF ~~CP~~

Ciuchini et al. (“pre-UTFit” paper),2000



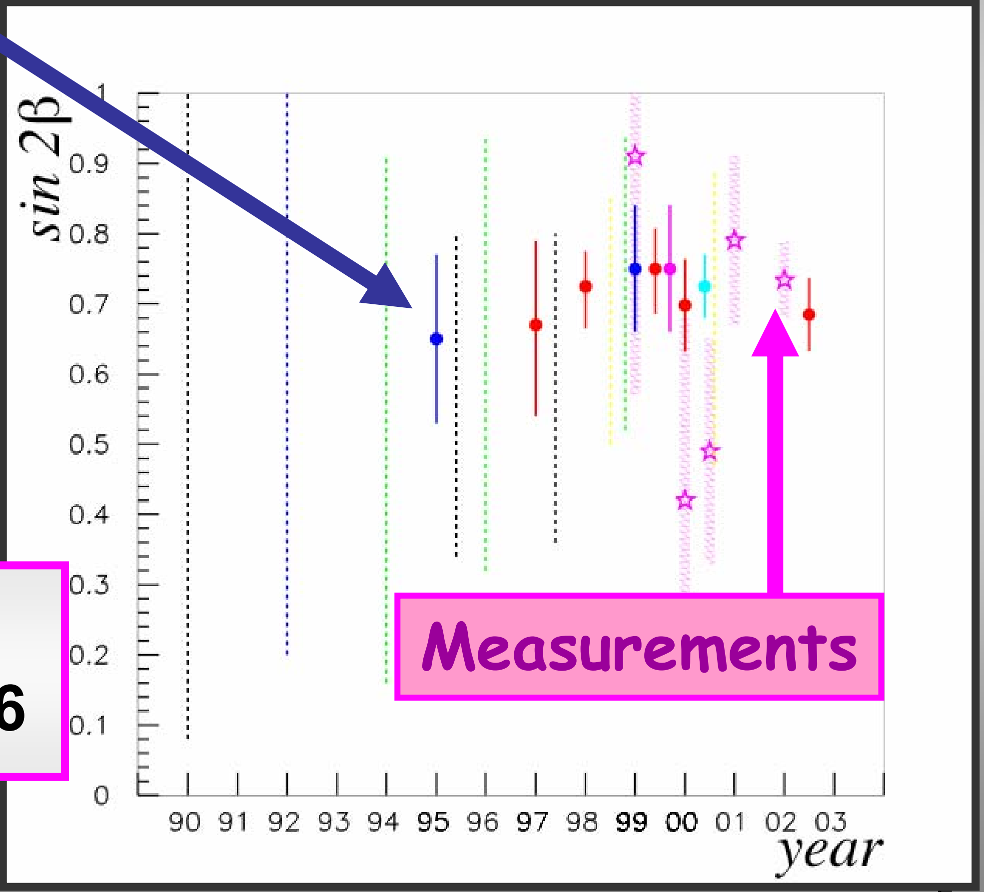
2) PREDICTION OF Sin2β

Predictions exist since 1995

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

Ciuchini et al.,2000:
$\sin 2\beta_{UTA} = 0.698 \pm 0.066$

ICHEP 2006:
$\sin 2\beta_{J/\psi\ K0} = 0.675 \pm 0.026$



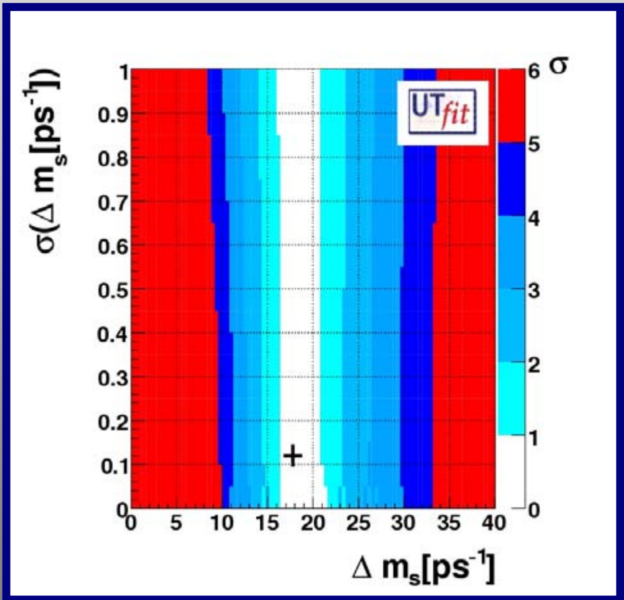
3) PREDICTION OF Δm_s

Ciuchini et al.,2000:

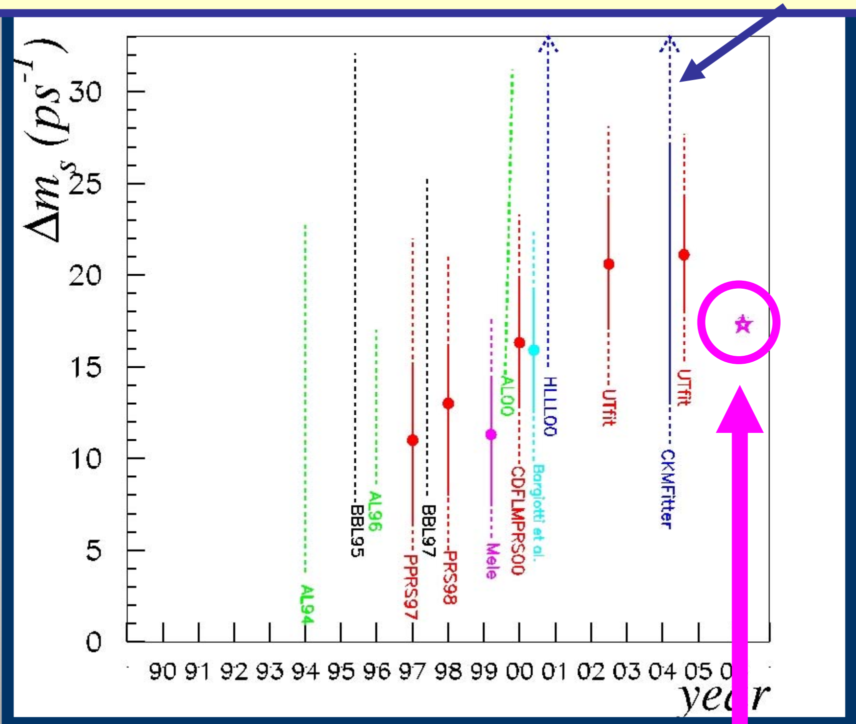
$\Delta m_s = (16.3 \pm 3.4)\ ps^{-1}$

UTFit Coll.,2006:

$\Delta m_s = (18.4 \pm 2.4)\ ps^{-1}$



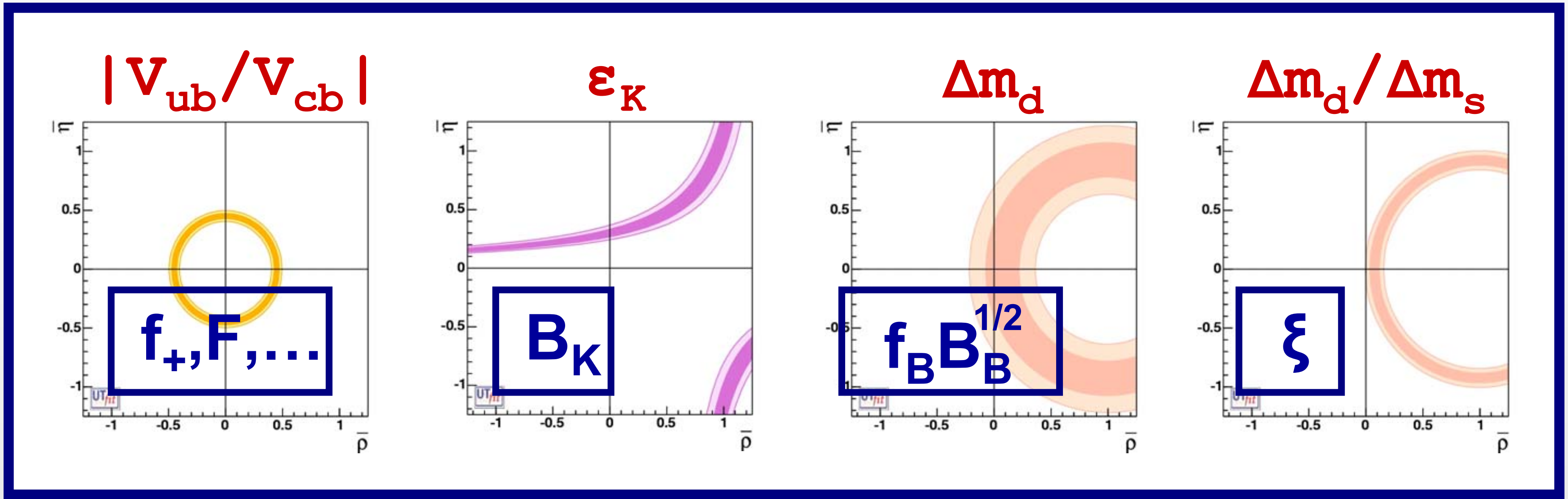
The predicted range was very large in the frequentistic CKMFitter approach



CDF, 2006:

$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ ps^{-1}$

THE LATTICE INPUT PARAMETERS



QUENCHING vs. UNQUENCHING

Nf=0 most of the calculations

Nf=2 few calculations

Nf=2+1 one/two calculations

QUENCHING vs. UNQUENCHING

Nf=0 most of the calculations
Nf=2 few calculations
Nf=2+1 one/two calculations

Quenched calculations: unsatisfactory because Nf=0. But:

- other systematic uncertainties well under control (non-perturbative renormalization, continuum extrapolation,…)
- the results checked by many groups, using various gauge and quark lattice actions

QUENCHING vs. UNQUENCHING

Nf=0 most of the calculations
Nf=2 few calculations
Nf=2+1 one/two calculations

Quenched calculations: unsatisfactory because Nf=0. But:

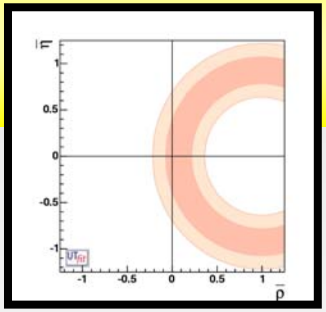
- other systematic uncertainties well under control (non-perturbative renormalization, continuum extrapolation,…)
- the results checked by many groups, using various gauge and quark lattice actions

Unquenched calculations: sound for being unquenched. But:

- dynamical quarks much heavier than the physical up and down quarks
- the consequences of the fourth-root trick (non-locality,…) are not clear
- non-perturbative renormalization is not carried out
- the results have not been checked by different groups.

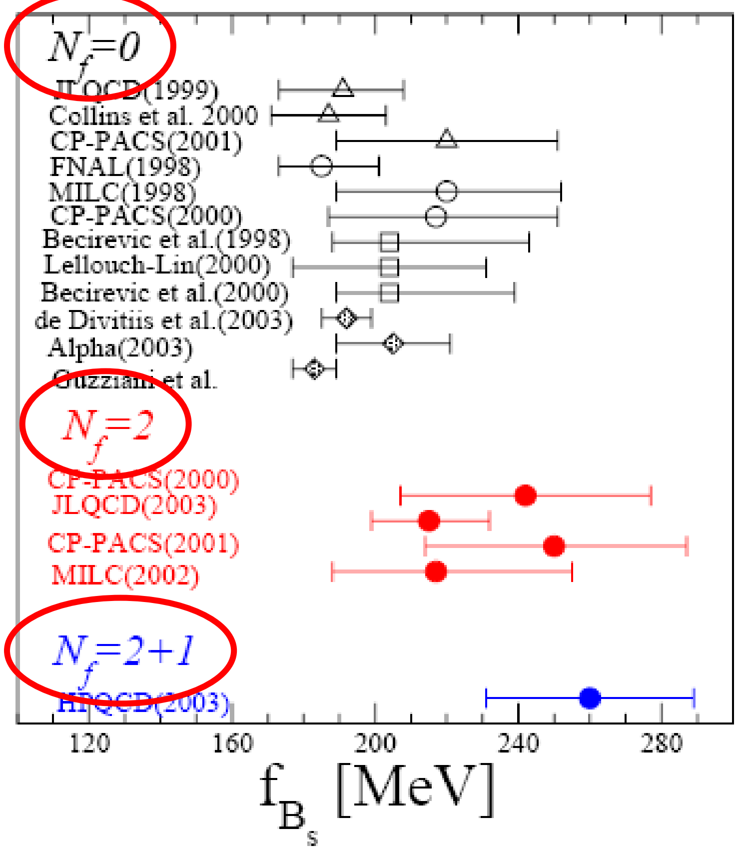
Unquenching is a work in progress

$B_{d,s}$ mixing: 1) f_{Bs}



The SM prediction for Δm_s relies on the lattice determination of f_{Bs}.

Onogi@Latt'06

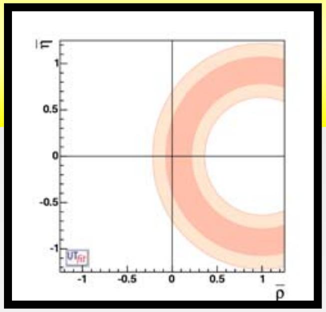


- The slight difference between Nf=2 and Nf=0 results depends on the quantity used to set the lattice scale

- There is some discrepancy (~1σ) between the Nf=2+1 result of HPQCD and the Nf=2 JLQCD result

- Is this difference the effect of the strange sea quark or of an (underestimated) systematic error?

$B_{d,s}$ mixing: 1) f_{Bs}

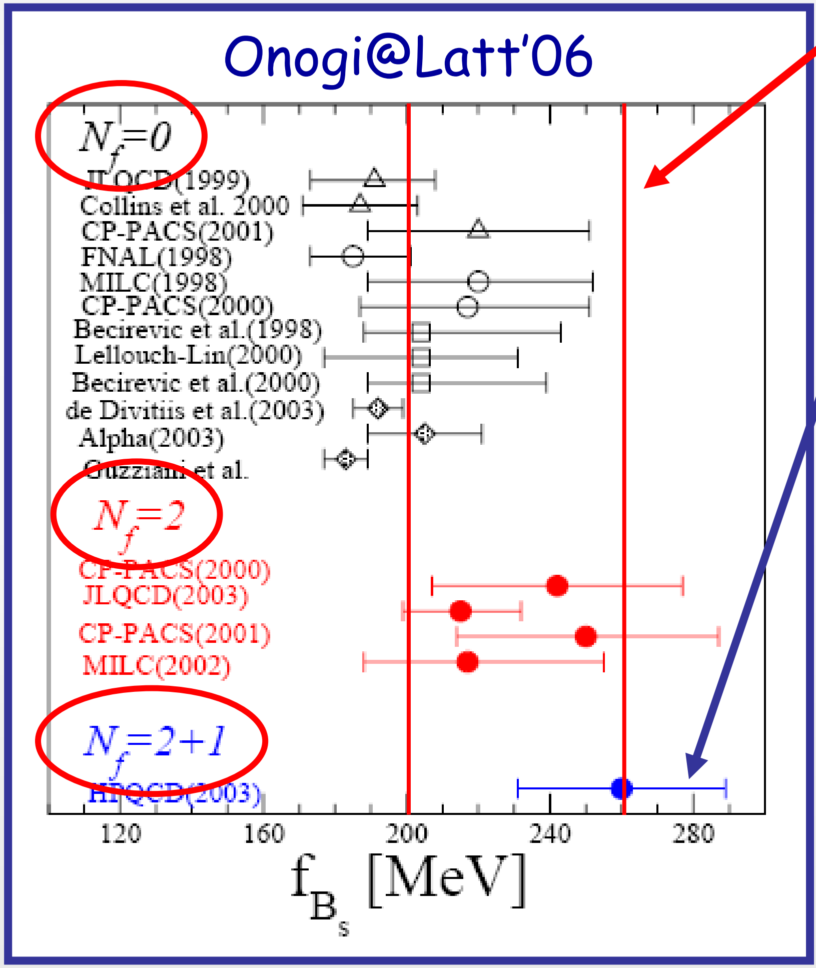


Recent lattice "averages" are:

f_{Bs} = 230 ± 30 MeV
Hashimoto@ICHEP'04

f_{Bs} = 260 ± 29 MeV
Okamoto@LATT'05
Onogi@LATT'06

HPQCD



If the difference is due to the strange sea quark effect then we should only consider the Nf=2+1 result. But:

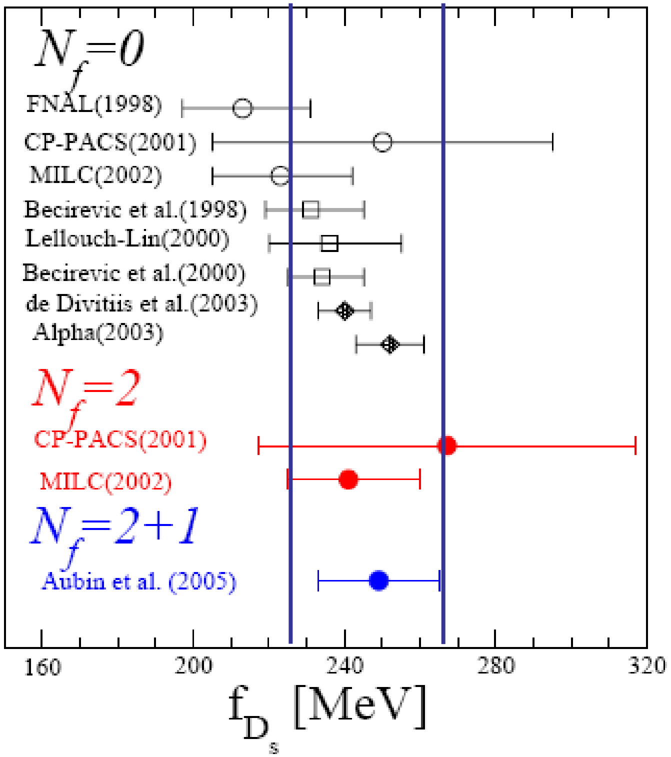
i) Nf=0 << Nf=2 < Nf=2+1

ii) $m_s >> m_{u,d}$

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

Important test for Lattice QCD

Onogi@Latt'06



Results from ICHEP06:

$f_D = (222 \pm 17 \pm 3)$ MeV

$f_{Ds} = (280 \pm 12 \pm 6)$ MeV

$f_{Ds}/f_D = 1.26 \pm 0.11 \pm 0.03$

Lattice QCD averages

$f_{Ds} = (245 \pm 20)$ MeV , $f_{Ds}/f_D = 1.23 \pm 0.06$

$B_{d,s}$ mixing: 2) f_{Bs}/f_B and ξ

f_B and therefore the ratio f_{Bs}/f_B are affected by the "potentially large" **effect of chiral logarithms**:

Recent history of ξ

"Old" estimates (<2002):

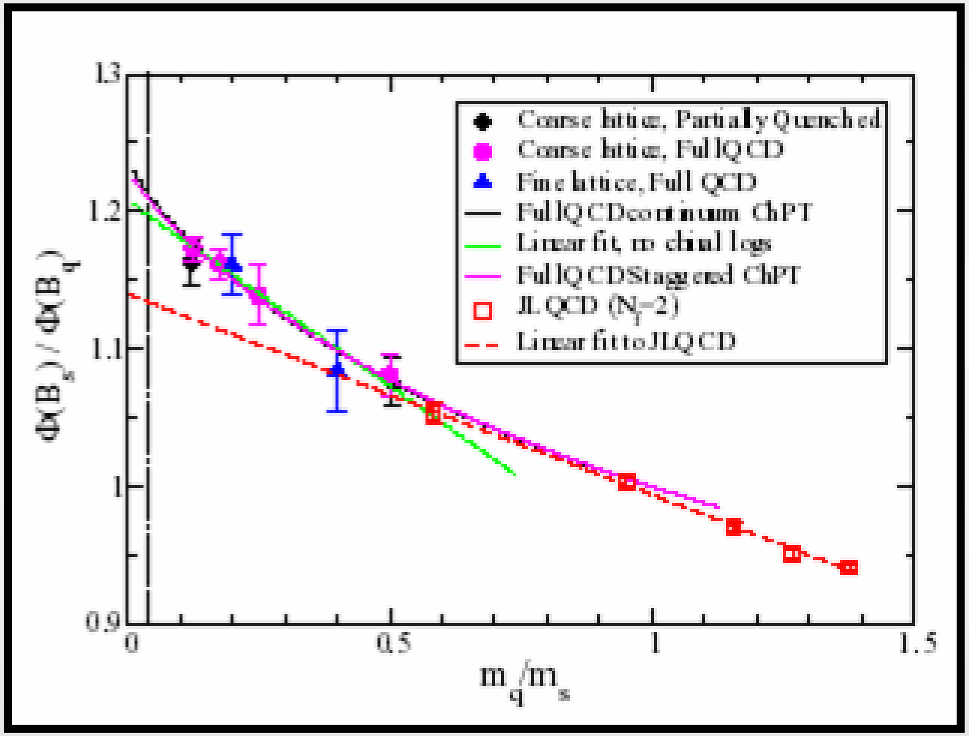
$f_{Bs}/f_B \approx 1.14 - 1.18$

Kronfeld and Ryan (2002)

$f_{Bs}/f_B = 1.32 \pm 0.10$

HPQCD (2005)

$f_{Bs}/f_B = 1.20 \pm 0.03$



But the present estimate still relies on a single calculation. Further determinations at low quark masses are required.

B_d and B_s mixing: 3) $B_{d,s}$

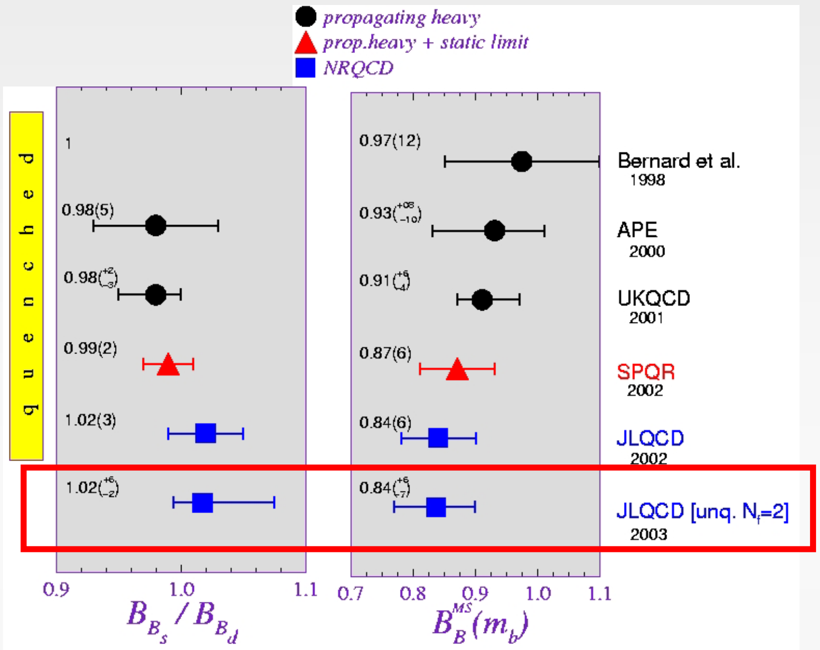
- No large chiral logs effects

- The Nf=2 result and a preliminary Nf=2+1 result consistent with quenched estimates

- Combining the Nf=2 result with the Hashimoto's averages of decay constants one gets:

$$f_{Bs}\sqrt{B_{Bs}} = 262 \pm 35 \text{ MeV}$$

$$\xi = 1.23 \pm 0.06$$

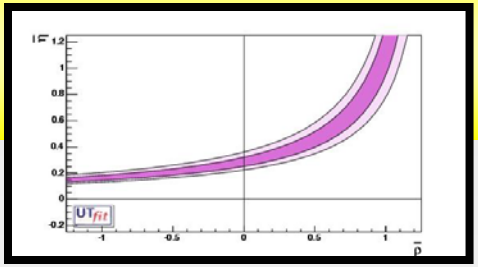


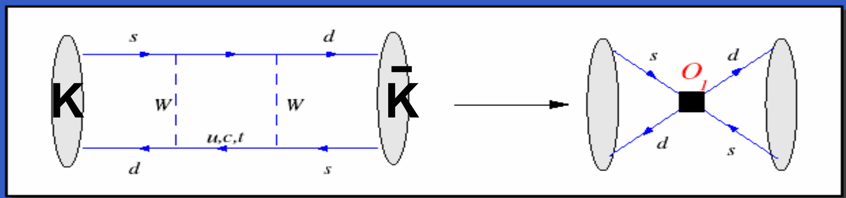
Preliminary Nf=2+1 HPQCD@Lattice06:

$$f_{Bs}\sqrt{B_{Bs}} = 281 \pm 21 \text{ MeV}$$

$$\xi = 1.25 \pm 0.05$$

$K-\bar{K}$ mixing: ε_K and B_K





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

QUENCHED ERROR

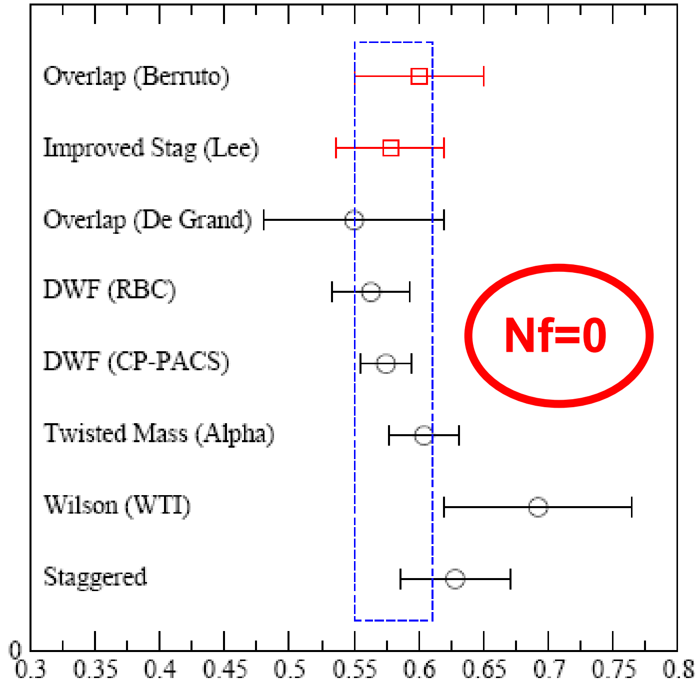
$$B_K = 0.58 \pm 0.03 \pm 0.06$$

$$\hat{B}_K = 0.79 \pm 0.04 \pm 0.09$$

C.Dawson@Latt'05

$\hat{B}_K = 0.90 \pm 0.20$ (Gavela et al.) 1987

C.Dawson@Latt'05

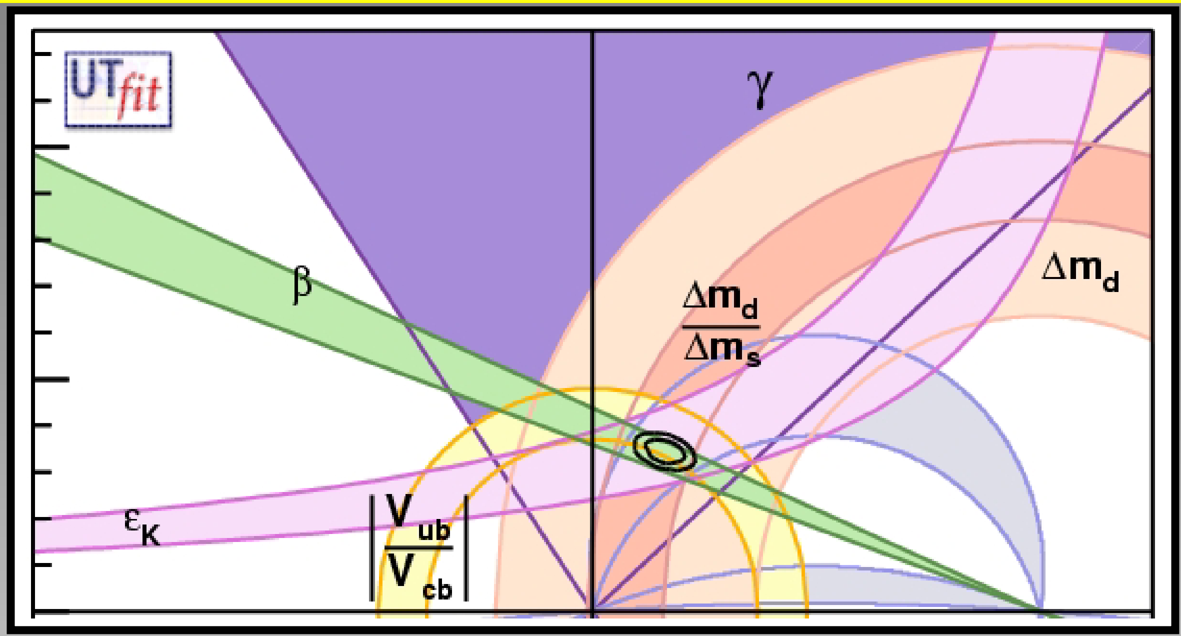


$B_K = 0.50 \pm 0.02_{\text{Stat.}} \pm ??$ Nf=2, RBC

$B_K = 0.62 \pm 0.14$ Nf=2+1 HPQCD & UKQCD

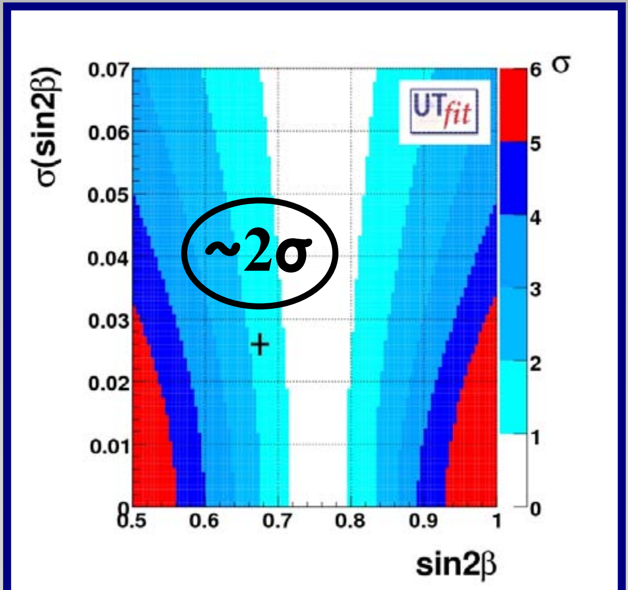
b->u decays and the V_{ub} puzzle

There is some tension in the fit, particularly between sin2β and V_{ub}

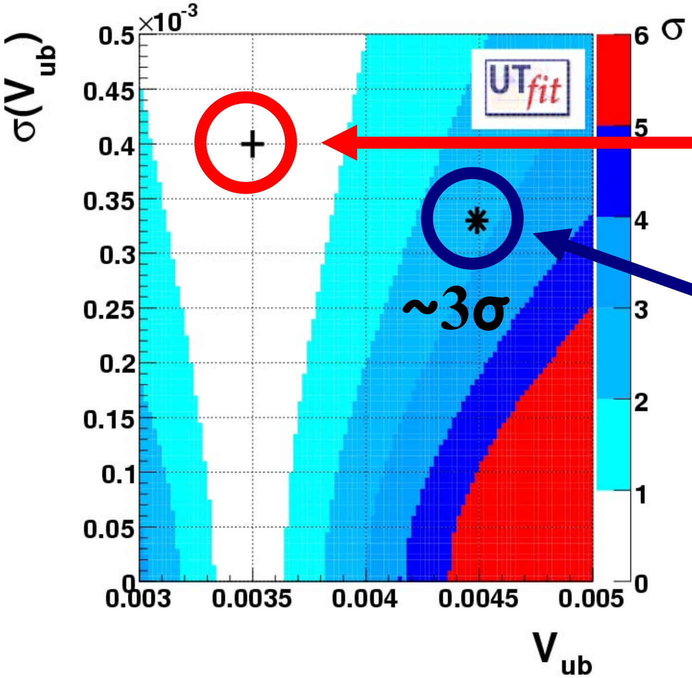


Sin2β = 0.675 ± 0.026
from the direct measurement

Sin2β = 0.755 ± 0.039
from the rest of the fit



The tension is between the inclusive V_{ub} and the rest of the fit



EXCLUSIVE

$V_{ub}^{excl.} = (35.0 \pm 4.0)\ 10^{-4}$

Form factors from LQCD and QCDSR

INCLUSIVE

$V_{ub}^{incl.} = (44.9 \pm 3.3)\ 10^{-4}$

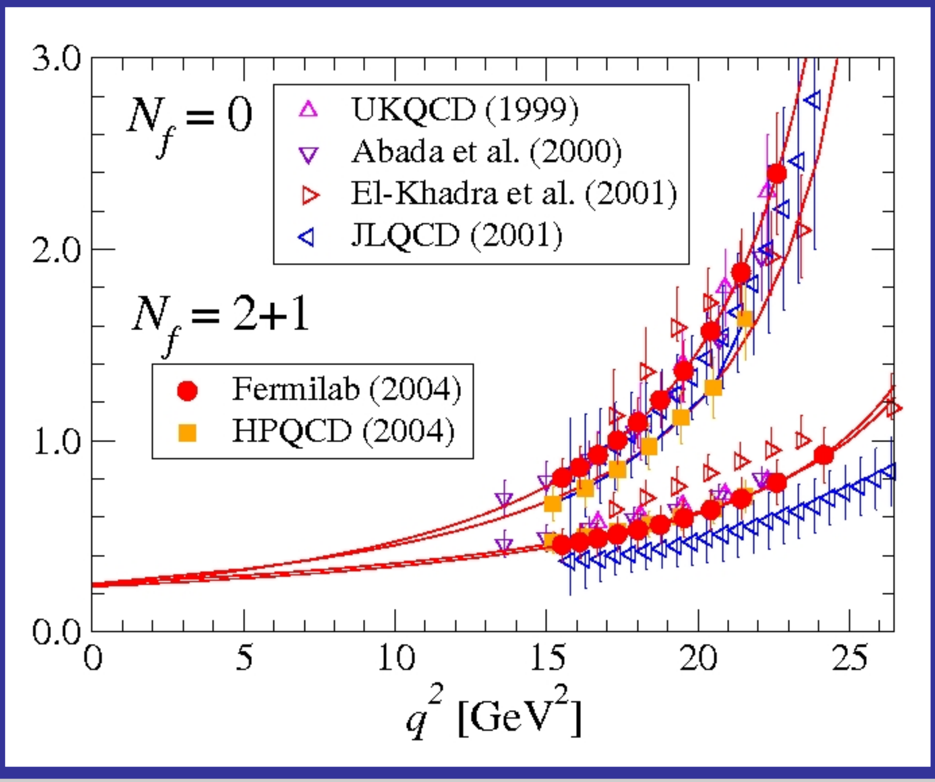
Model dependent (BLNP, DGE,..)
Non perturbative parameters most not from LQCD (fitted from experiments)

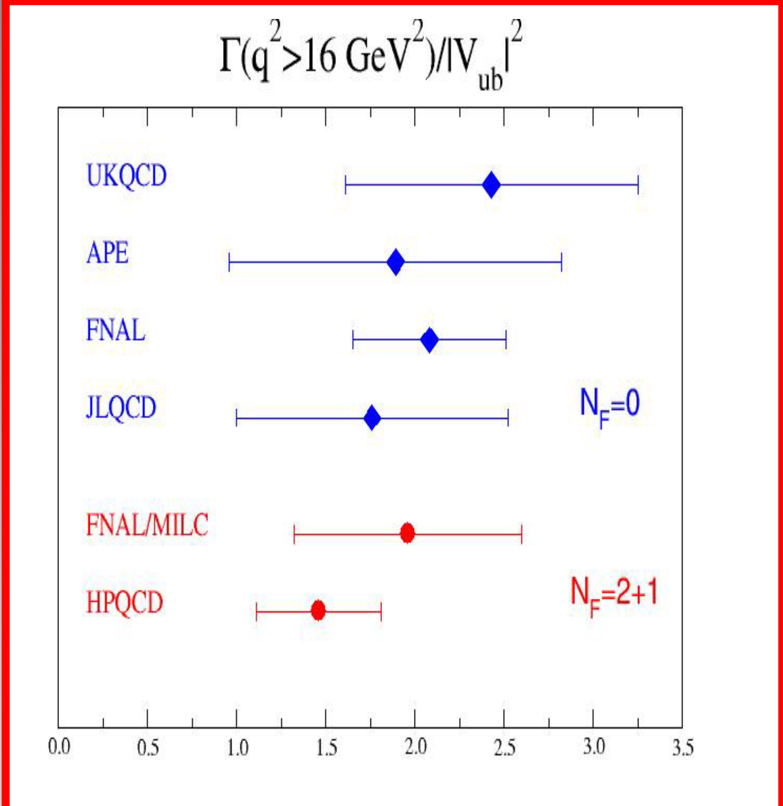
A New Physics effect is unlikely in this tree-level process

➡ i) Statistical fluctuation

ii) Problem with the theoretical calculations and/or the estimate of the uncertainties

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

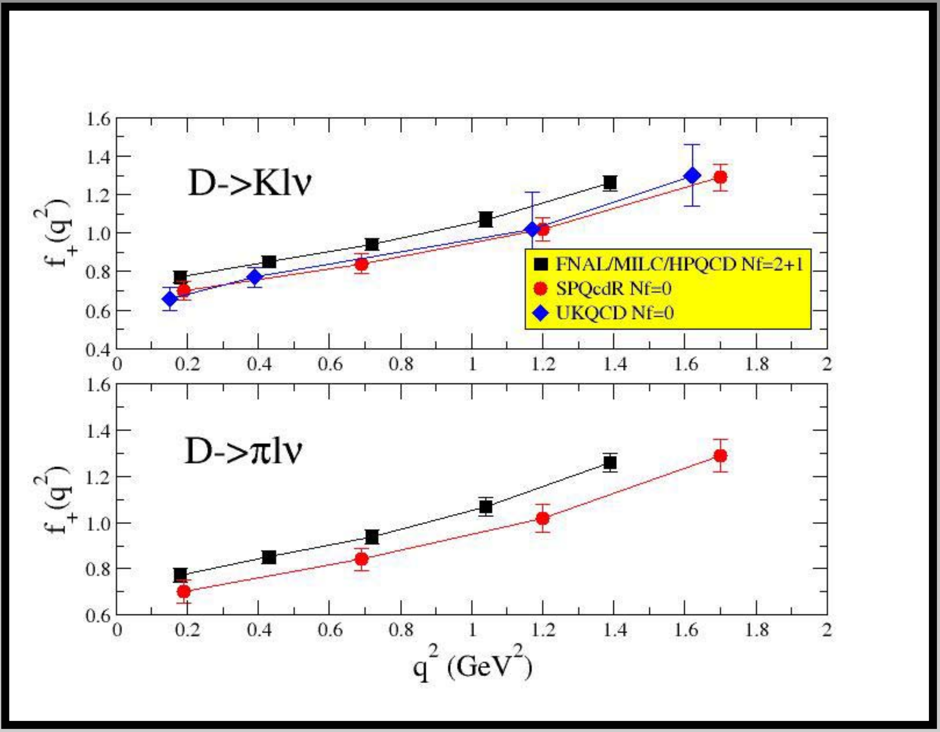


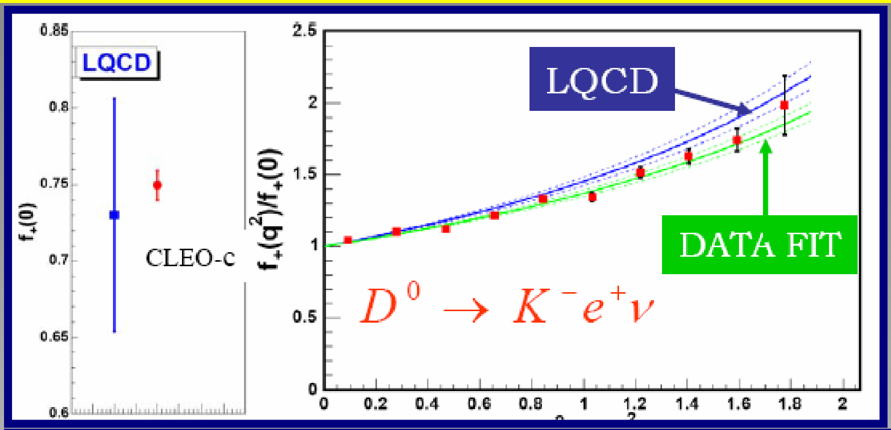


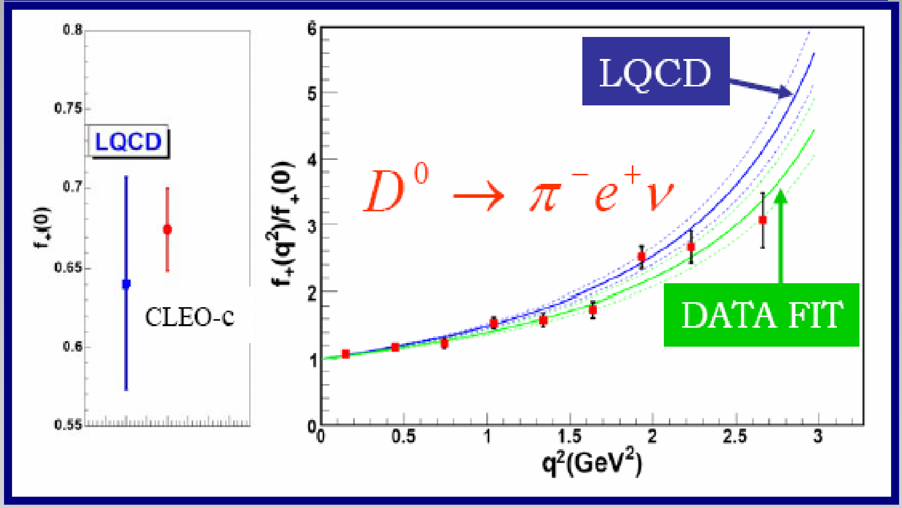
4 calculations with Nf=0

2 calculations with Nf=2+1

Semileptonic D→K/π lν decays
An important test for Lattice QCD



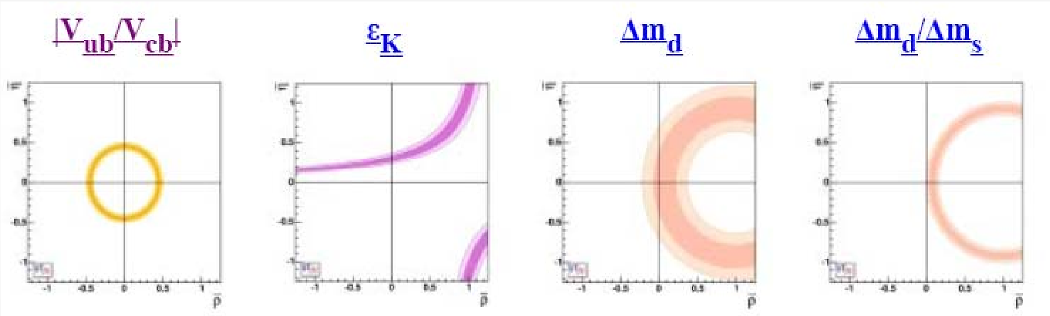


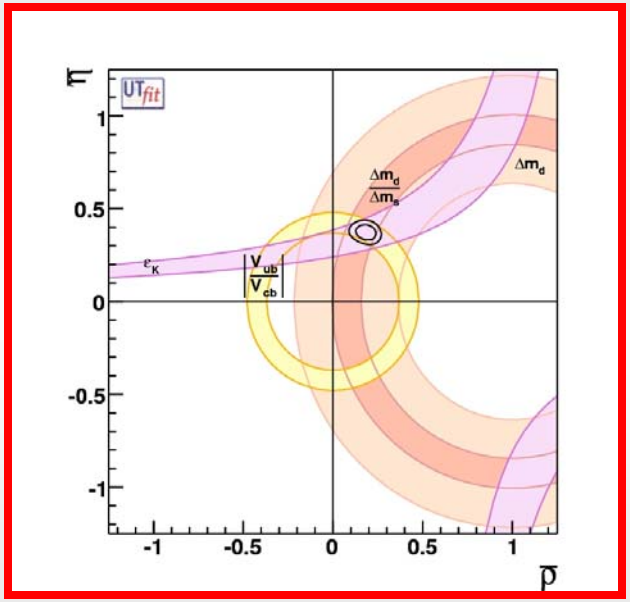


More (and possibly more accurate) LQCD calculations are needed, also for the D → Vector channel

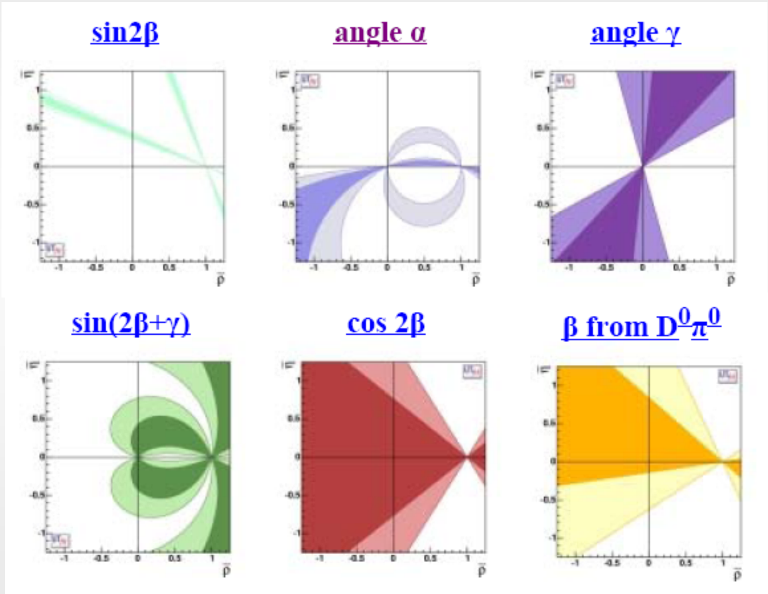
"EXPERIMENTAL" DETERMINATION OF THE LATTICE PARAMETERS

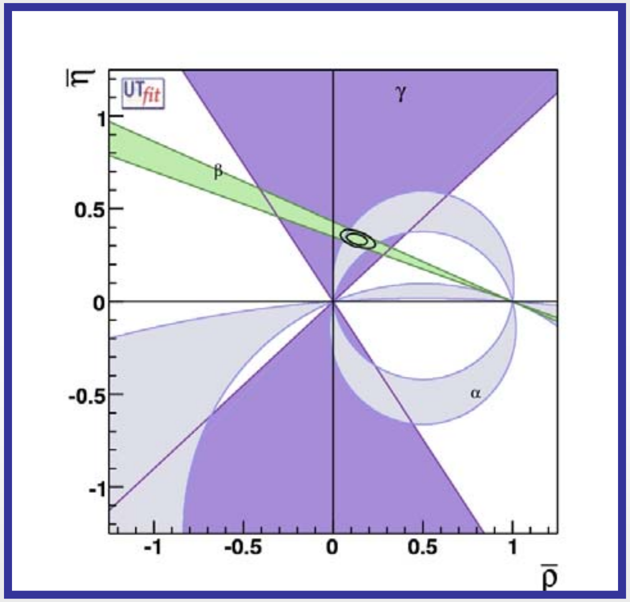
UT-LATTICE





UT-ANGLES





"EXPERIMENTAL" DETERMINATION OF LATTICE PARAMETERS

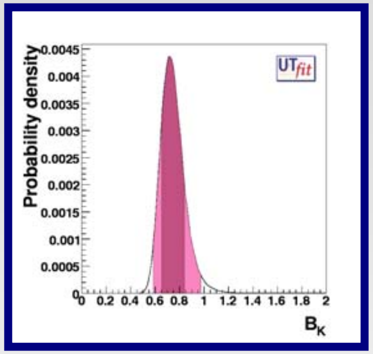
The new measurements of Δm_s and $BR(B \to \tau \nu_\tau)$ allows a simultaneous fit of the hadronic parameters:

$$|\varepsilon_K| = C_\varepsilon A^2 \lambda^6 \bar{\eta} \left[-\eta_1 S(x_c) + \eta_2 S(x_t) \left(A^2 \lambda^4 (1-\bar{\rho}) \right) + \eta_3 S(x_c, x_t) \right] \hat{B}_K$$

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} M_W^2 \eta_B S_0(x_t) |V_{tq}|^2 \hat{B}_{B_q} f_{B_q}^2$$

$$BR(B^- \to \tau^- \bar{\nu}_\tau) = f_B^2 |V_{ub}|^2 \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2} \right)^2 \tau_B$$

Take the angles from experiments and extract $f_{Bs}\sqrt{B_{Bs}}$, $f_B\sqrt{B_{Bd}}$ or ξ and f_B

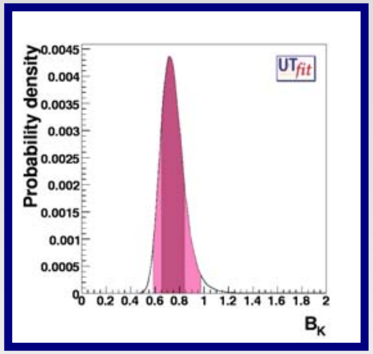


$\hat{B}_K = 0.75 \pm 0.09$

UTA

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

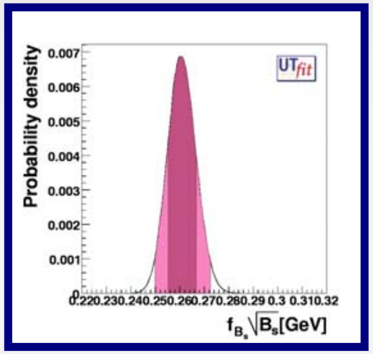
Lattice
[Dawson]



$\hat{B}_K = 0.75 \pm 0.09$ — UTA

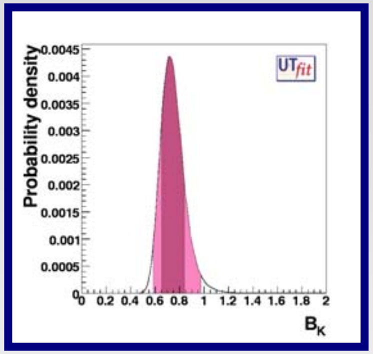
$\hat{B}_K = 0.79 \pm 0.04 \pm 0.08$ — Lattice [Dawson]

2% !



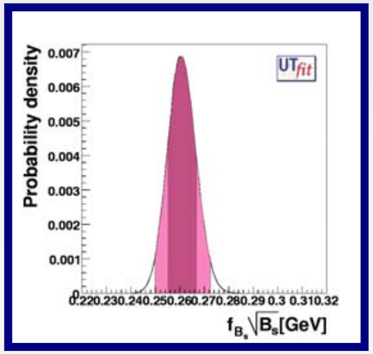
$f_{Bs}\sqrt{B_{Bs}} = 261 \pm 6$ MeV — UTA

$f_{Bs}\sqrt{B_{Bs}} = 262 \pm 35$ MeV — Lattice [Hashimoto]

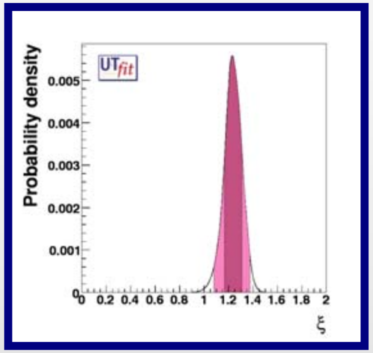


$\hat{B}_K = 0.75 \pm 0.09$	UTA
$\hat{B}_K = 0.79 \pm 0.04 \pm 0.08$	Lattice [Dawson]

2% !

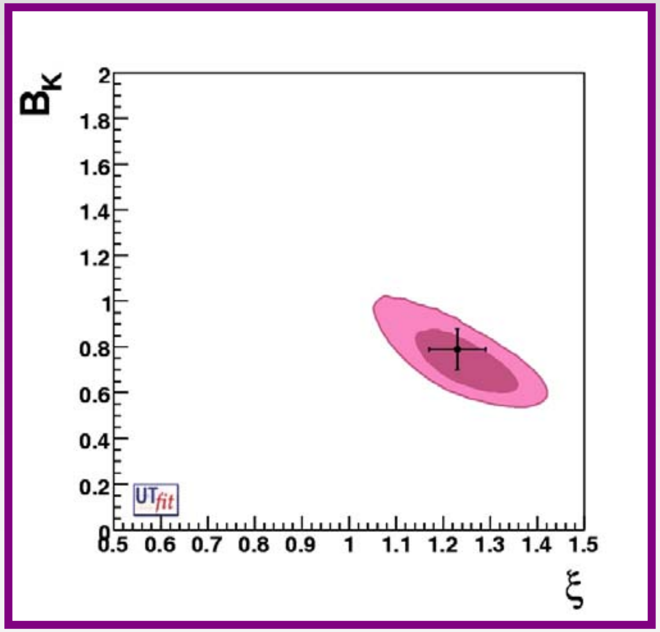


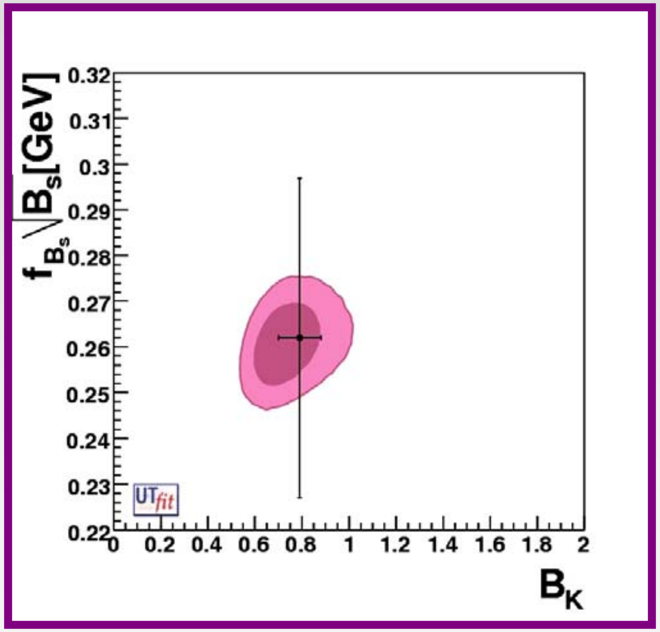
$f_{Bs}\sqrt{B_{Bs}} = 261 \pm 6$ MeV	UTA
$f_{Bs}\sqrt{B_{Bs}} = 262 \pm 35$ MeV	Lattice [Hashimoto]

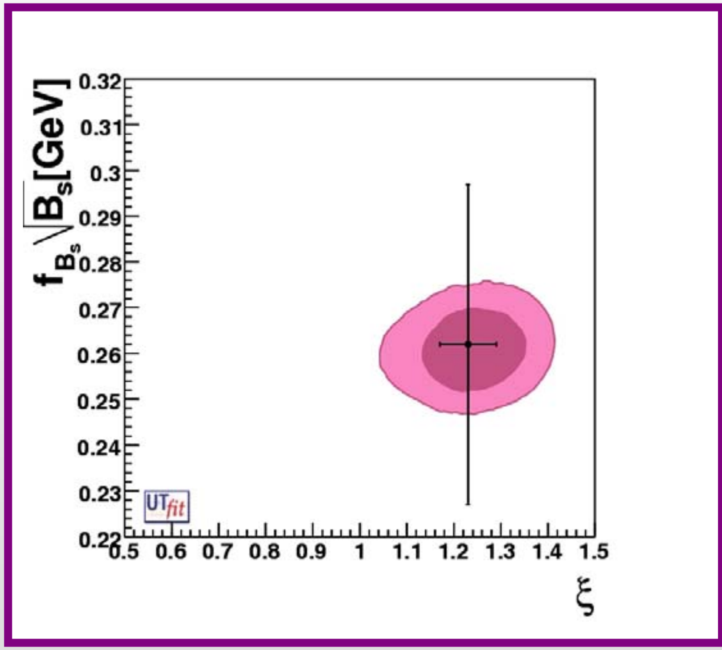


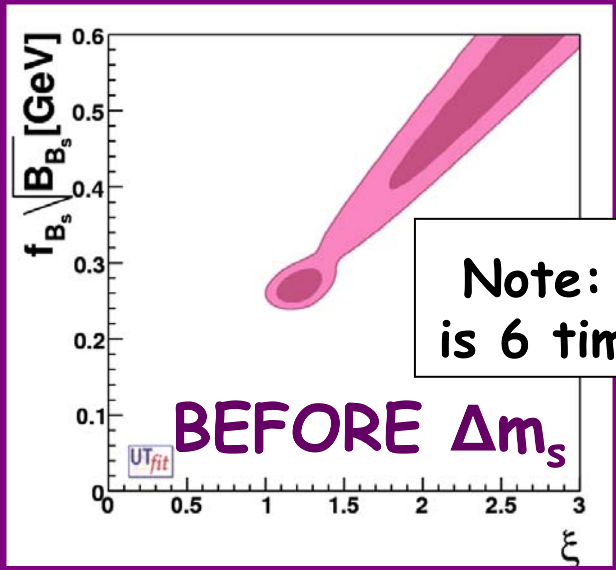
$\xi = 1.24 \pm 0.08$	UTA
$\xi = 1.23 \pm 0.06$	Lattice [Hashimoto]

The agreement is spectacular!









BEFORE Δm_s

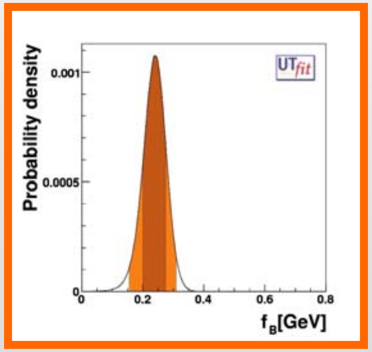
Note: the scale is 6 times larger!!

The extraction of the decay constants can be obtained by using the Lattice QCD determinations of the B parameters: $\hat{B}_{Bd} = \hat{B}_{Bs} = 1.28 \pm 0.05 \pm 0.09$

$f_{Bs} = 229 \pm 9$ MeV	$f_B = 190 \pm 14$ MeV	UTA
$f_{Bs} = 230 \pm 30$ MeV	$f_B = 189 \pm 27$ MeV	Lattice

f_B can also be extracted using V_{ub} and the recent determination of the leptonic branching fraction:

$Br(B \to \tau\nu_\tau) = (1.31 \pm 0.48) \times 10^{-4}$ Belle + BaBar average



$f_B = 237 \pm 37$ MeV

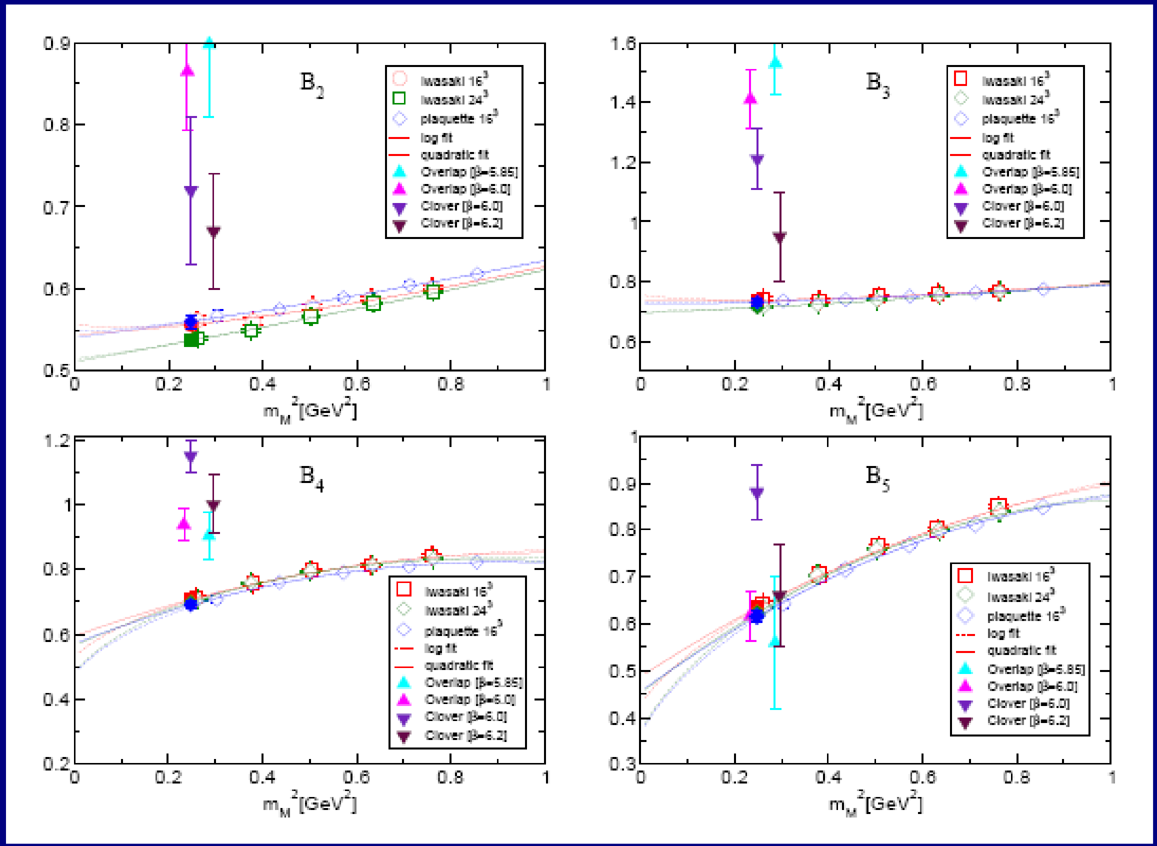
(Vub from the UTA)

You may have got the impression that Lattice QCD calculations are becoming irrelevant for the UTA. But this is not true…

They are crucial to perform the UTA in the context of New Physics scenarios.

K-$\bar{\text{K}}$ MIXING IN NP MODELS

$$\mathcal{O}_1 = \bar{s}^a \gamma_\mu (1-\gamma_5) d^a \bar{s}^b \gamma_\mu (1-\gamma_5) d^b,$$
$$\mathcal{O}_2 = \bar{s}^a (1-\gamma_5) d^a \bar{s}^b (1-\gamma_5) d^b,$$
$$\mathcal{O}_3 = \bar{s}^a (1-\gamma_5) d^b \bar{s}^b (1-\gamma_5) d^a,$$
$$\mathcal{O}_4 = \bar{s}^a (1-\gamma_5) d^a \bar{s}^b (1+\gamma_5) d^b,$$
$$\mathcal{O}_5 = \bar{s}^a (1-\gamma_5) d^b \bar{s}^b (1+\gamma_5) d^a$$



Clover
APE 1999

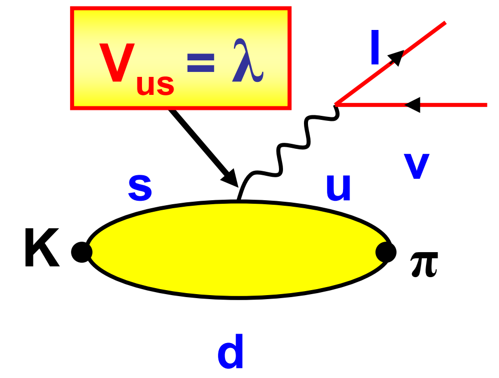
Overlap
Babich et al. 2006

Domain wall
CP-PACS 2006

V_{us} AND Kl3 DECAYS

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

The most stringent unitarity test



$$\Gamma(K \to \pi l \nu(\gamma)) = \frac{G_F^2 M_K^5}{192\pi^3} \cdot C_K^2 |V_{us}|^2 \; |f_+^{K^0\pi^-}(0)|^2 I_l S_{ew} (1+\delta_l)^2$$

Ademollo-Gatto:

$$f_+(0) = 1 - O(m_s - m_u)^2$$

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

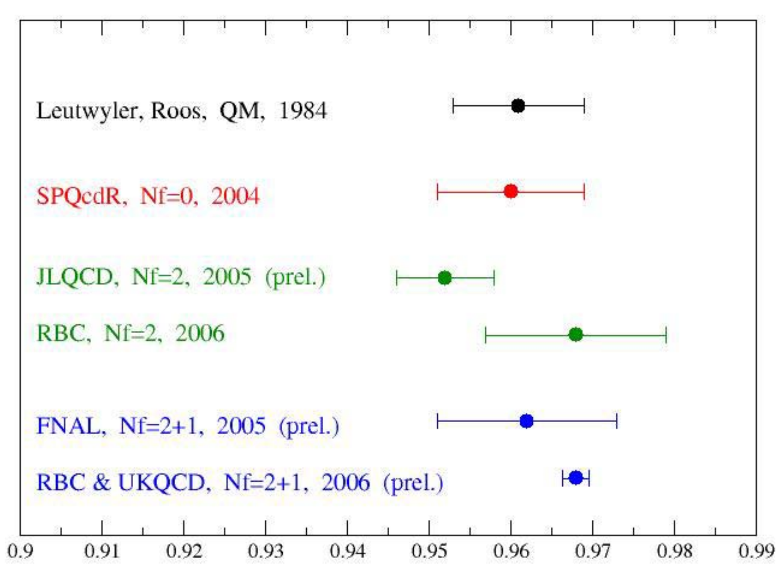
Vector Current Conservation

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

THE LARGEST UNCERTAINTY

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

Several lattice QCD calculations in the last 2 years:



$$f_+(0) = 0.960 \pm 0.009$$

The old quark model calculation by Leutwyler and Roos has been now confirmed in QCD.

But lattice QCD calculations have the capability to further improve the theoretical accuracy

CONCLUSIONS

- The accuracy of lattice QCD calculation is improving, particularly because the quenched approximation is being abandoned. But unquenching is still a work in progress…

- A special effort must be done for the semileptonic form factors necessary to the extraction of V_{ub}

- Extraordinary experimental progresses allow the extraction of several hadronic quantities from the data, assuming the SM. The results are is very good agreement with LQCD determinations

- LQCD calculations of many hadronic parameters are required to study flavor physics in the framework of New Physics scenarios.