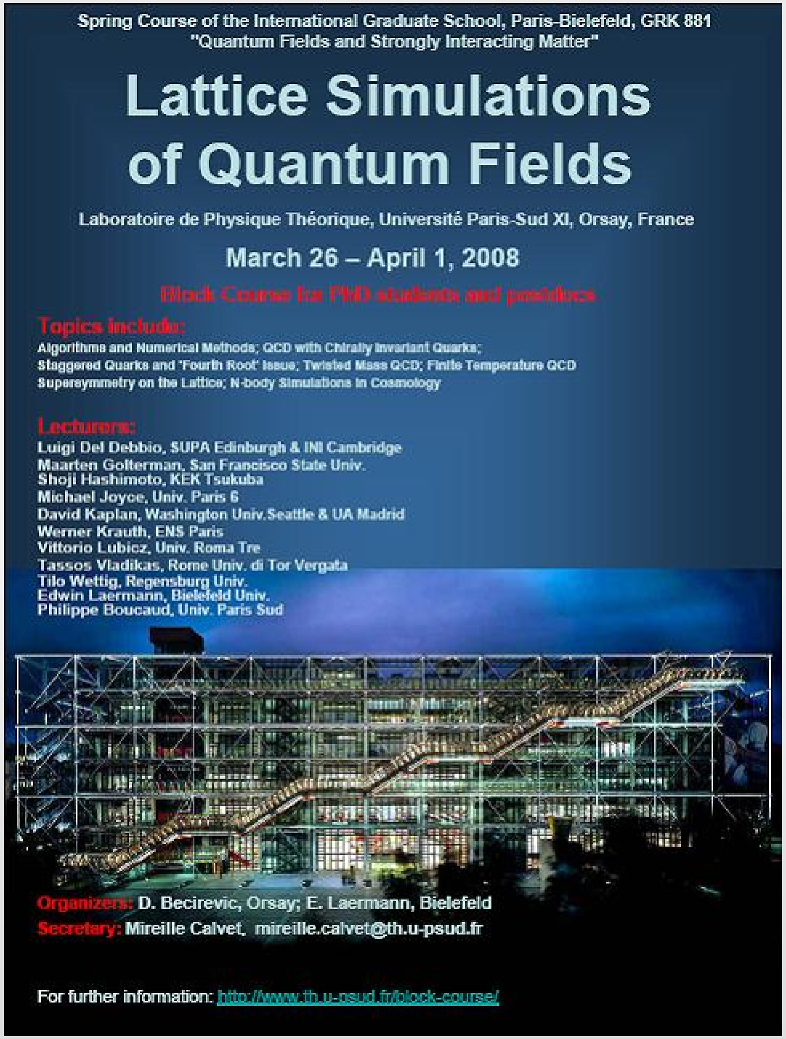
PHYSICS OF FLAVOURS AND LATTICE QCD


Spring Course of the International Graduate School, Paris-Bielefeld, GRK 881
"Quantum Fields and Strongly Interacting Matter"

Lattice Simulations of Quantum Fields

Laboratoire de Physique Théorique, Université Paris-Sud XI, Orsay, France

March 26 – April 1, 2008

Block Course for PhD students and postdocs

Topics include:
Algorithms and Numerical Methods; QCD with Chirally Invariant Quarks;
Staggered Quarks and 'Fourth Root' issue; Twisted Mass QCD; Finite Temperature QCD
Supersymmetry on the Lattice; N-body Simulations in Cosmology

Lecturers:
Luigi Del Debbio, SUPA Edinburgh & INI Cambridge
Maarten Golterman, San Francisco State Univ.
Shoji Hashimoto, KEK Tsukuba
Michael Joyce, Univ. Paris 6
David Kaplan, Washington Univ.Seattle & UA Madrid
Werner Krauth, ENS Paris
Vittorio Lubicz, Univ. Roma Tre
Tassos Vladikas, Rome Univ. di Tor Vergata
Tilo Wettig, Regensburg Univ.
Edwin Laermann, Bielefeld Univ.
Philippe Boucaud, Univ. Paris Sud

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For further information: http://www.th.u-psud.fr/block-course/

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UNIVERSITÉ PARIS-SUD 11

1. FLAVOUR PHYSICS AND ITS MOTIVATIONS

- Introduction to Flavour Physics
- Evidence of physics beyond the Standard Model
- Flavour physics as a probe of New Physics

2. FLAVOUR PHYSICS AND LATTICE QCD

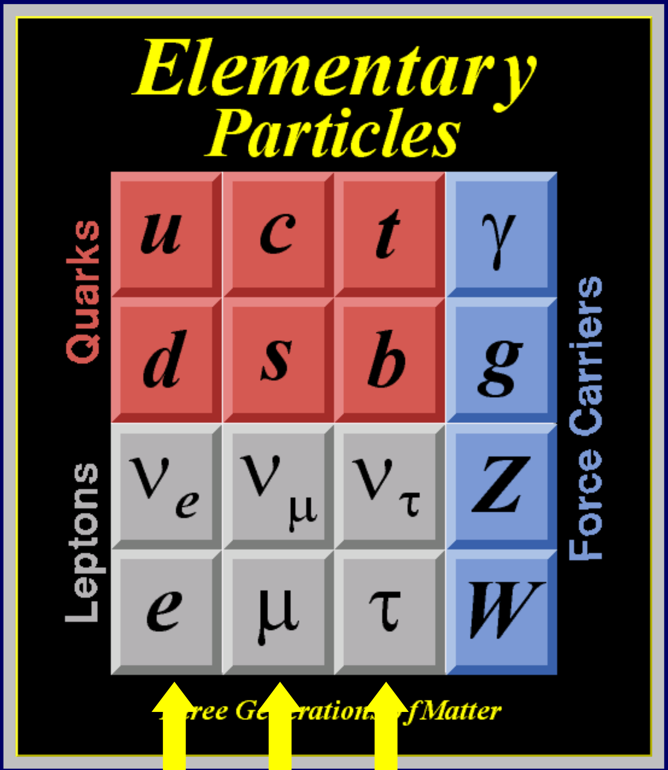
- The "precision era" of Lattice QCD (why now)
- Vus and the first row unitarity test
- Lattice QCD and the Unitarity Triangle Analysis
- The UTA beyond the Standard Model:
  evidence of New Physics in Bs mixing

NEW !!

- Lattice QCD and quark masses

Appendix: a simple model of Flavour Physics

FLAVOUR PHYSICS



6 Flavours
3 Families

- **FLAVOUR**: elementary fermions (matter particles) are 6 flavours of quarks and 6 of leptons

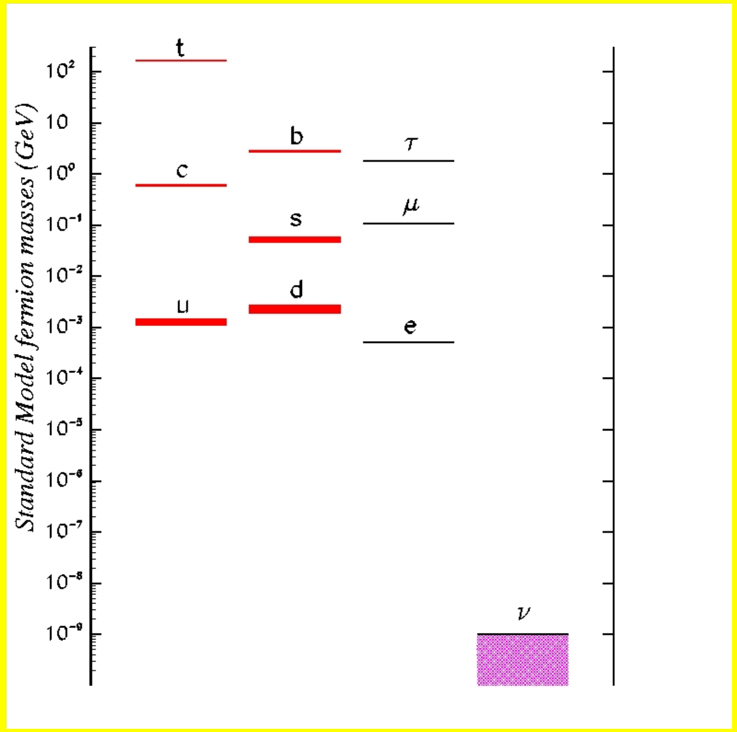
- **MASSES**: Quarks and leptons come in 3 families which only differ for particle masses

- **MIXING**: In the Standard Model flavour is conserved by electromagnetic and strong interactions. Only weak interactions (charged currents) change flavour ⟶ CKM matrix and CP violation

Flavor physics is (well) described but not explained in the Standard Model

A large number of free parameters in the flavor sector: 10 parameters in the quark sector (6 m_q + 4 CKM), 12 in the lepton sector (with massive neutrinos)

- Why 3 families with their observed particle content?
- Why the spectrum of quarks and charged leptons covers 5 orders of magnitude? ($m_q \sim Yv \sim G_F^{-1/2}$...)
- What give rise to the pattern of quark mixing and the magnitude of CP violation?



THE FLAVOUR SYMMETRY:

The Standard Model fermions consist of 3 families with (Q_L, L_L, U_R, D_R, E_R).

The largest unitary group that commutes with the gauge group is:

$$G_F = U(3)^5 = [SU(3)\otimes U(1)]^5$$

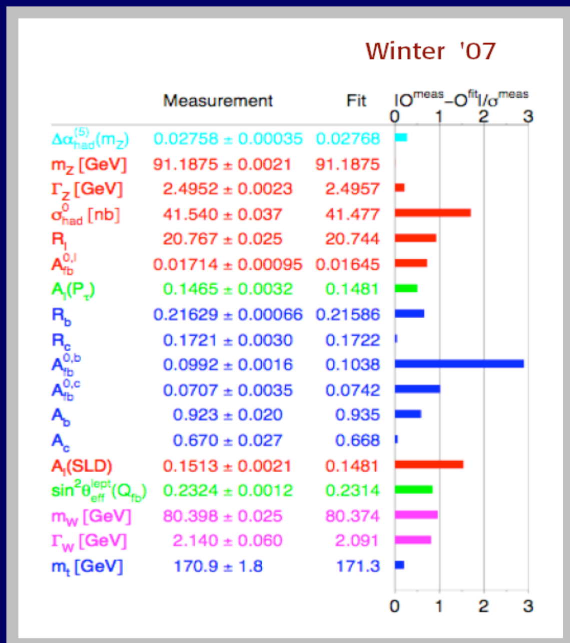
In the SM, G_F is broken by the Yukawa interactions:

$$G_F \rightarrow U(1)_B \otimes U(1)_L \otimes U(1)_Y$$

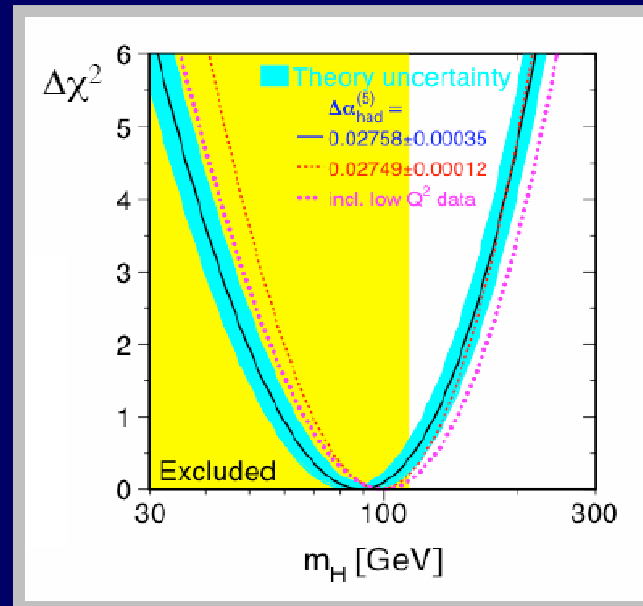
WHICH IS THE ORIGIN OF FLAVOUR SYMMETRY BREAKING?

[Note: also the mechanism of gauge symmetry breaking is unknown. A single elementary Higgs doublet is only the simplest solution.]

Experiments show that the **Standard Model with a light Higgs** provides a quite successful description of electro-magnetic, weak and strong interactions (the gauge sector), up to the Fermi scale



χ^2/d.o.f.=18/13



114 GeV < m_H < 182 GeV @ 95% CL

Despite this success, we have both theoretical and observational evidence of

PHYSICS BEYOND THE STANDARD MODEL

EVIDENCE OF PHYSICS BEYOND THE STANDARD MODEL

PROBLEMS OF THE STANDARD MODEL AND EVIDENCE OF NEW PHYSICS

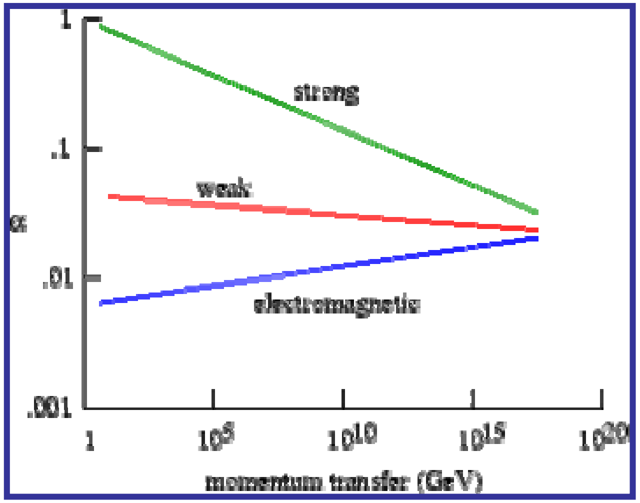
- Gravity ($M_{Planck} = (\hbar c/G_N)^{1/2} \approx 10^{19}$ GeV)
- Theory of flavour
- Hierarchy ($M_{EW} << M_{Planck}$)
- Unification of couplings ($M_{GUT} \approx 10^{15}$-10^{16} GeV)
- Neutrino masses ($M \approx M_{GUT}$)
- Dark matter ($\Omega_M \approx 0.3$)
- Vacuum energy ($\Omega_\Lambda \approx 0.7$)
- Baryogenesis
- Inflation ($\Omega_{tot} = 1, \ldots$)

} Clash with the Standard Model of cosmology (Dark matter, Vacuum energy, Baryogenesis, Inflation)

UNIFICATION OF COUPLINGS

The running of gauge couplings provides strong indication of unification.

Precise unification, however, fails in the SM [$\alpha_s(M_Z) \approx 0.073$] (compatible with low energy SUSY)



GUT are very appealing for several reasons

- Unity of forces
- Unity of quark and leptons (different directions in G)
- Family Q-numbers (in SO(10) a whole family in 16)
- Charge quantization (Q_d = -1/Nc = -1/3)
- B and L non conservation

NEUTRINO MASSES

The existence of neutrino masses and mixings is well established. But neutrinos are massless in the SM and the simple extension of the SM with the inclusion of ν_R looks very unnatural.

Neutrino masses are really special: $m_t / (\Delta m_{atm}) \sim 10^{12}$

A natural solution: ν's are Majorana particles and get masses through L violating interactions suppressed by a large scale M

$$O_5 = \frac{(HL)^T \lambda (HL)}{M} + h.c.$$

The seesaw mechanism is a specific realization

$$m_\nu \sim \frac{m^2}{M}$$

For $m_\nu \sim 0.05$ eV and $m \sim v \sim 200$ GeV ➡

$$M \sim 10^{15}\ \text{GeV} \sim M_{GUT}$$

DARK MATTER

$\Omega_{tot} = \Omega_{vac} + \Omega_{mat} + \Omega_{rad} + \ldots = 1.005(6)$

Inflation: $\Omega_{tot} = 1$
Flat Universe

$\Omega_{vac} \approx 0.7$, $\Omega_{mat} \approx 0.3$ Both problematic !

$(\Omega_{rad} \approx 10^{-5})$

$\Omega_{mat} = \Omega_b + \Omega_{dm}$

$\Omega_b \approx 0.05$, $\Omega_{dm} \approx 0.23$

Baryonic matter (Ω_b) — Dark matter (Ω_{dm}) (i.e. non-luminous and non-absorbing)

More than 80% of matter is non baryonic dark matter !!

NO CANDIDATES IN THE SM. ν'S ARE NOT RELEVANT FOR DM

Most of DM should be cold ← All hot DM would have not permitted galaxies to form

(Cold) Hot DM ≡ (Non) relativistic at the onset of galaxy formation

WIMP (LSP:neutralino, Extra-d.:LKP,...), SWIMP (gravitino), axions, axinos,...

Many NP candidates

Remarkably: $M_{WIMP} \sim M_{EW}$

VACUUM ENERGY

$$\Omega_{vac} \approx 0.7$$

The scale of the cosmological constant is a big mystery

- In QFT the energy density of the vacuum receives an infinite contribution from the zero-point energies of the various modes of oscillation. For a bosonic scalar field:

$$H_b = \sum_p (a_p^\dagger a_p + \frac{1}{2})\varepsilon_p \quad \Rightarrow \quad \langle 0| H_b |0\rangle = \frac{1}{2}\sum_p \varepsilon_p$$

Fermionic s=1/2 fields give a negative contribution:

$$H_f = \sum_p (b_p^\dagger b_p + c_p^\dagger c_p - 1)\varepsilon_p \quad \Rightarrow \quad \langle 0| H_f |0\rangle = -\sum_p \varepsilon_p$$

• The scale of the zero-point energy density is provided by the cutoff:

$$\rho_{vac} = \frac{1}{V} \langle 0|\, H \,|0\rangle \sim \frac{1}{V} \sum_{\varepsilon_p < \Lambda_{cut}} \varepsilon_{\mathbf{p}} \overset{(\varepsilon_p = cp)}{\approx} \Lambda_{cut}^4 / (\hbar c)^3$$

If $\Lambda_{cut} \sim M_{Planck}$ ➡ $\rho_{vac} \sim 10^{123}\, \rho_{vac}^{obs}$

Exact SUSY would solve the problem:

$$\langle 0|\, H \,|0\rangle = (\tfrac{1}{2} n_b - n_f) \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} = 0$$

But SUSY is broken

Assuming $\Lambda_{SUSY} \approx 1\ \mathrm{TeV}$:

$$\rho_{vac} \approx \Lambda_{SUSY} / (\hbar c)^3 \sim 10^{59}\, \rho_{vac}^{obs}$$

The problem of the scale of the cosmological constant has found no solution so far

Modification of gravity (extra-dim), leak of vacuum energy to other universes (wormholes),...

Baryogenesis (matter-antimatter asymm.)

- So far, no primordial anitimatter has been observed in the Universe. Up to distances of order 0.1–1 Gpc the Universe consists only of matter. [1Gpc = 3.2 10^9 light years. Observable universe: $H_0 \sim 10$ Gpc]
- A very plausible assumption is that the big bang produces an equal number of quarks and antiquarks

WHEN AND WHY ANTIMATTER DISAPPEARED ?

The Sakharov conditions: (1967)	In the SM:
1) Baryon number violation	Istanton process
2) C and CP violation	Weak interactions
3) Departure from thermal equilibrium	EW phase transition

In the SM, for $m_H \geq 80$ GeV, the e.w. phase transition does not provide enough thermal instability necessary for baryogenesis

$\not{CP}$ generated by the CKM mechanism is irrelevant for baryogenesis

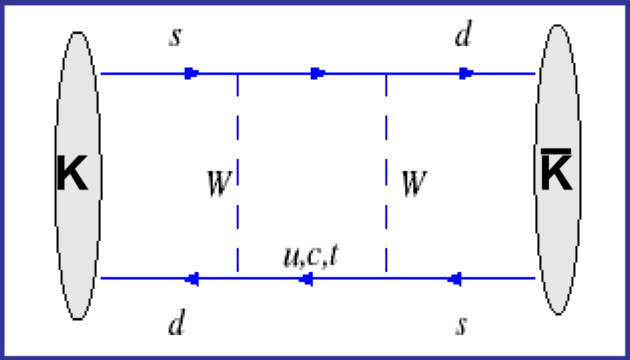
➡ Non-standard $\not{CP}$ is a necessary ingredient for baryogenesis

FLAVOUR PHYSICS AS A PROBE OF NEW PHYSICS

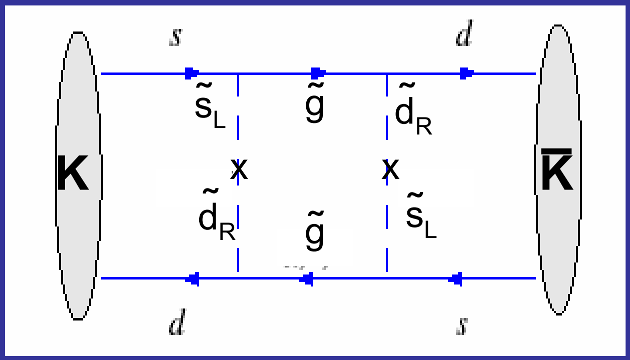
INDIRECT SEARCHES OF NEW PHYSICS

Most of **beyond SM physics** can be explained by New Physics models (**SUSY**, **GUT**, **Extra-dim.**,...).

New Physics enters the low-energy processes through quantum loops → **Flavor Physics could allow us to discriminate among different New Physics scenarios**



Standard Model



New Physics

In the past, **the existence of the charm quark** or the **heaviness of the top quark** have been predicted **from the study of virtual effects** long before their experimental observation

THE STANDARD MODEL AS AN EFFECTIVE LOW-ENERGY THEORY

The great success of the SM up to energies of $O(\Lambda_{EW})$ scale tells us that **the SM** has to be recovered as **the low-energy limit of the New Physics theory**:

$$\mathcal{L}_{eff} = O(\Lambda^2)\mathcal{L}_2 + O(\Lambda)\mathcal{L}_3 + O(1)\mathcal{L}_4 + \quad \Big\} \text{ Standard Model: Renormalizable operators}$$

$$+ O(1/\Lambda)\mathcal{L}_5 + O(1/\Lambda^2)\mathcal{L}_6 + \ldots \quad \Big\} \text{ New Physics: suppressed by } O(1/\Lambda^{4-i})$$

$\mathcal{L}_2$: Boson masses φ^2. In the SM $\delta m_H^2 \sim O(\Lambda^2) \rightarrow$ Hierarchy problem

$\mathcal{L}_3$: Fermion masses $\bar{\psi}\psi$. Protected by chiral symmetry: $\Lambda \rightarrow m \log\Lambda$

$\mathcal{L}_4$: Renormalizable interactions: $\bar{\psi}\gamma A\psi$

$\mathcal{L}_5$: Neutrino masses: $\nu^T\nu H^2, \ldots$ $\mathcal{L}_6$: $(\bar{\psi}\gamma\psi)(\bar{\psi}\gamma\psi), \ldots$

Which is the scale of New Physics?

THE "NATURAL" NEW PHYSICS SCALE

$$m_H^2 = m_{bare}^2 + \delta m_H^2$$

$$\delta m_H^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 + \ldots \approx (0.3\ \Lambda)^2$$

But radiative corrections indicate $m_H \sim 100$ GeV

→ The "natural" cut-off is $\Lambda = O(1\ \text{TeV})$

New Physics must be very "special":
it is so close, but its effects are not directly visible

The SM works too well both in
the electroweak and in the flavour sector

↓ THE LEP PARADOX

↓ THE FLAVOR PROBLEM

THE FLAVOUR PROBLEM

Consider the most general effective Hamiltonian for $\Delta F = 2$ processes:

$$\langle M | H_{\text{eff}}^{\text{NP}} | \bar{M} \rangle = \sum_{i,j} C_j(\Lambda)\, W_{ji}(\Lambda,\mu)\, \underbrace{\langle M | Q_i(\mu) | \bar{M} \rangle}$$

NEW PHYSICS SCALE

Complete basis of four-fermion operators

The $C(\Lambda)$ depend on the general properties of the NP model:

$$C_i(\Lambda) = a F_i / \Lambda^2$$

a = loop factor
F = flavour coupling

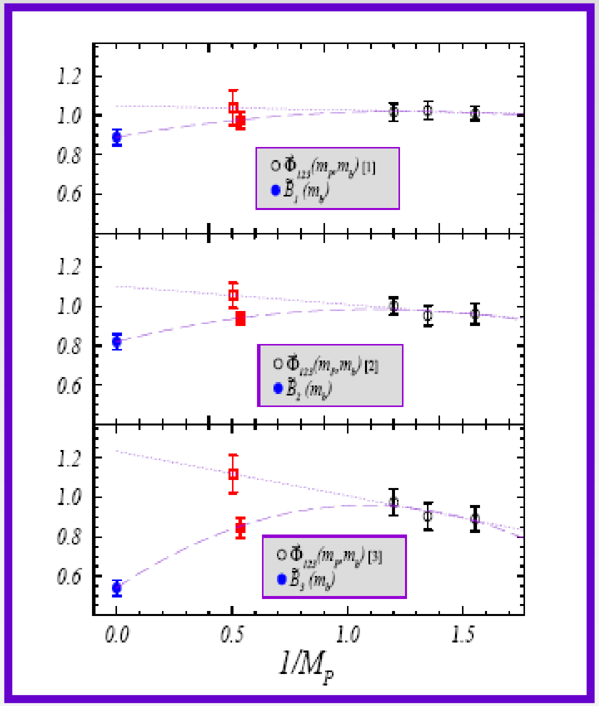
$C_i(\Lambda) = a/\Lambda^2$	Generic flavour structure
$C_1(\Lambda) = a F_{SM}/\Lambda^2$, $C_j(\Lambda) = 0$	Minimal Flavour Violation
$C_i(\Lambda) = a \lvert F_{SM} \rvert e^{i\varphi}/\Lambda^2$	Next-to-Minimal Flavour Violation

F_{SM} is the combination of CKM factors for the considered process

$a \sim 1$ for tree-level or strongly interacting NP

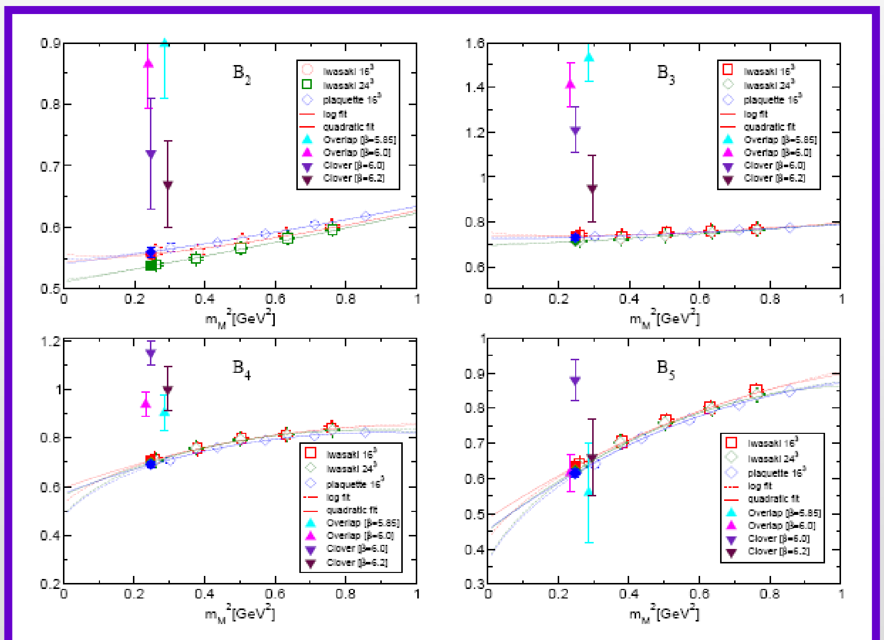
$a \sim \alpha_s$ or α_w loop-mediated strong or weak interacting contributions

Hadronic matrix elements from Lattice QCD



B-$\bar{B}$ MIXING

Becirevic et al., 2001



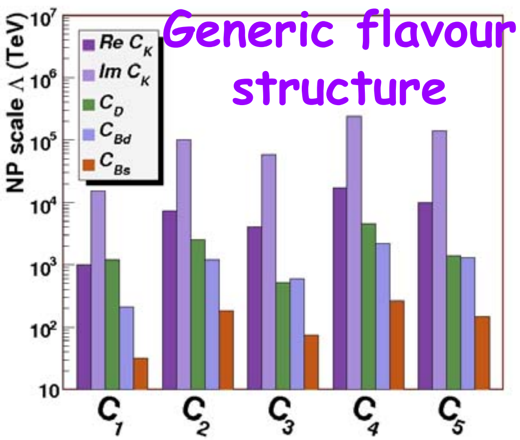
K-$\bar{K}$ MIXING

- APE 1999
- Babich et al. 2006
- CP-PACS 2006

Only few calculations !!

UTfit 0707.0636 [hep-ph]

Lower bound on Λ in TeV



Scenario	strong/tree	α_s-loop	α_w-loop
MFV	5	0.5	0.2
NMFV	62	6.2	2
General	24000	2400	800

THE “FLAVOUR PROBLEM”

NP contributions, particularly chirality flipping (LR) operators, are enhanced by the values of the hadronic matrix elements and by the RGE.

When these operators are allowed, particularly in the kaon sector, the NP scale is easily pushed beyond the TeV scale (and the LHC reach).

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NEW !!

- Lattice QCD and quark masses

Appendix: a simple model of Flavour Physics

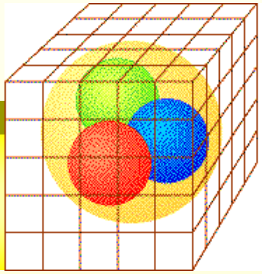
In the era of precision experimental flavour physics

ε_K	$(2.280 \pm 0.013)\ 10^{-3}$	0.6%
Δm_d	$(0.507 \pm 0.005)\ ps^{-1}$	1%
Δm_s	$(17.77 \pm 0.12)\ ps^{-1}$	0.7%
$\sin 2\beta$	0.668 ± 0.028	4%
$\|V_{us}\| f_+(0)$	0.21664 ± 0.00048	0.2%
…	…	…

… … …

we are also entering the era of

Precision LATTICE QCD



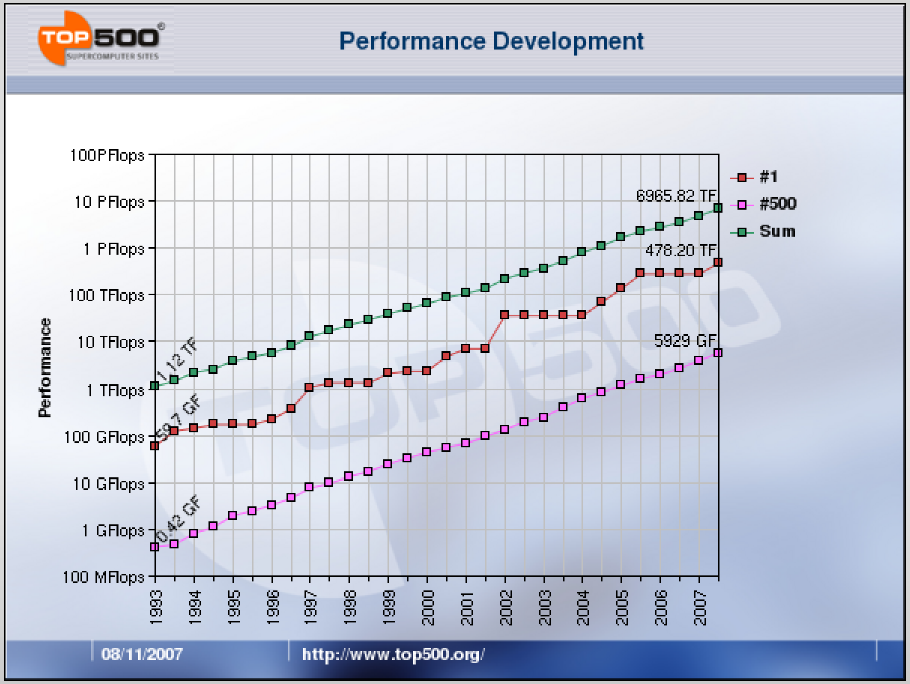
Unquenched calculations with relatively **low quark masses** are now being performed by **several groups** using **different approaches** (lattice action, renormalization,…).

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 today: ~ 1-30 TFlops

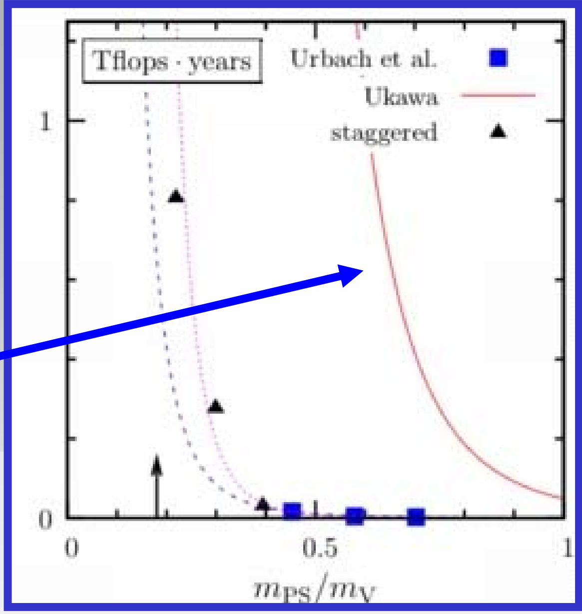
TeraFlops machines are required to perform unquenched simulations

CPU cost for Nf=2 Wilson fermions: [Del Debbio et al. 2006]

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

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

"The **Berlin wall** has been disrupted"



CPU cost (for Nf=2 Wilson fermions):

Ukawa 2001 (The Berlin wall):

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

Del Debbio et al. 2006:

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

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

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

V_{us} AND THE "FIRST ROW" UNITARITY TEST

1^{st} row: the most stringent unitarity test

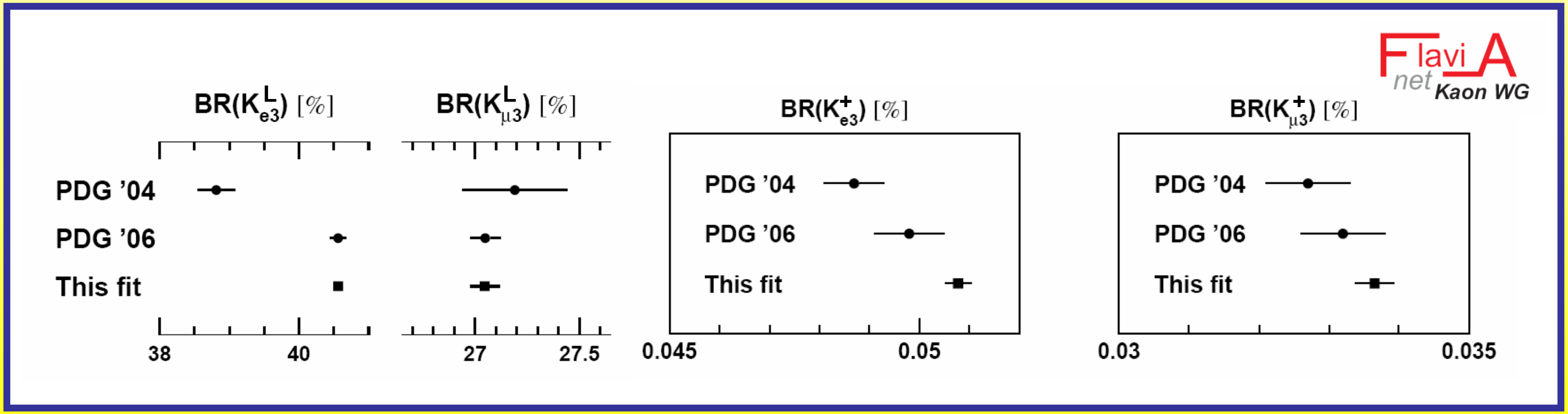
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Source:	Nuclear β-dec.	Kl3,Kl2	b→u semil.
Abs. error:	$5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$\sim 10^{-6}$

The PDG 2004 quoted a 2σ deviation from unitarity:

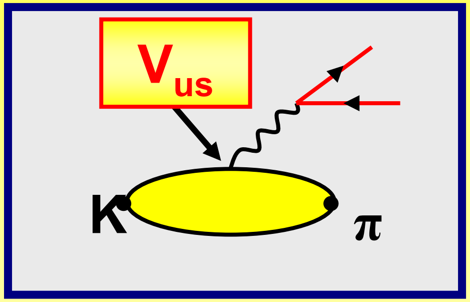
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0029 \pm 0.0015$$

Extraordinary experimental progress: the old PDG average for Vus has been superseded by the new results: KLOE ISTRA+ NA48 KTeV



Vus from Kl3 decays

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



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

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)

$f_4 = -0.016 \pm 0.008$

ChPT calculation of f_4 and model estimates

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

Post, Schilcher, 2001; Bijnens and Talavera, 2003

$C_{12}(\mu)$ and $C_{34}(\mu)$ can be determined (in principle) from the slope and the curvature of the scalar form factor. But experimental data are not accurate enough.

A model dependence must be introduced:

Leutwyler and Roos, $f_4^{LOC} = -0.016 \pm 0.008$ [Quark model]

Jamin et al., $f_4^{LOC} = -0.018 \pm 0.009$ [Dispersive analysis]

Cirigliano et al., $f_4^{LOC} = -0.002 \pm 0.008$ [1/Nc+Low resonance]

Lattice QCD

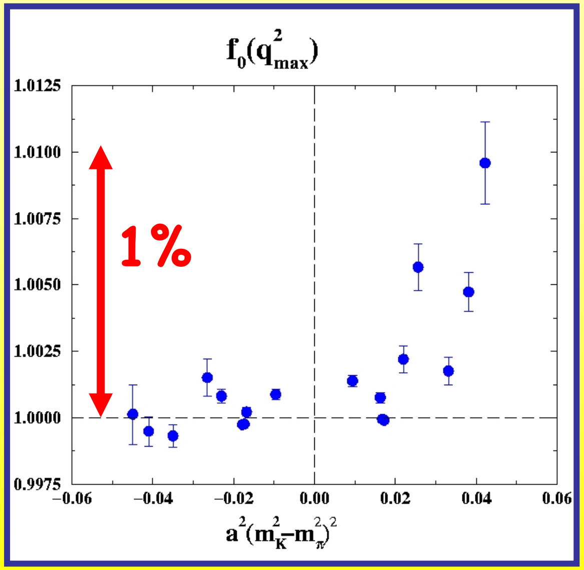
THE REQUIRED O(1%) PRECISION HAS BEEN REACHED

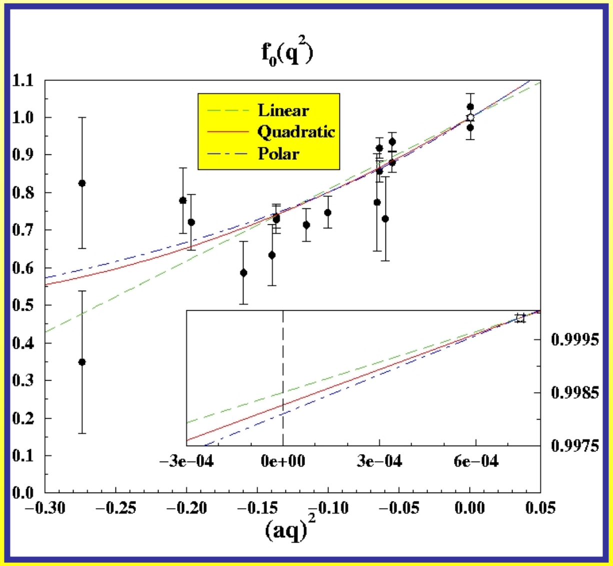
D.Becirevic, G.Isidori, V.L., G.Martinelli, F.Mescia, S.Simula, C.Tarantino, G.Villadoro. [NPB 705,339,2005]

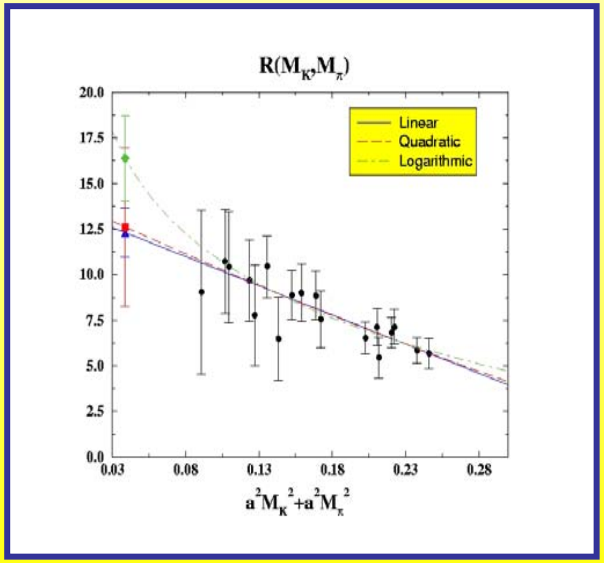
The basic ingredient is a double ratio of correlation functions:

[FNAL for B->D/D*]

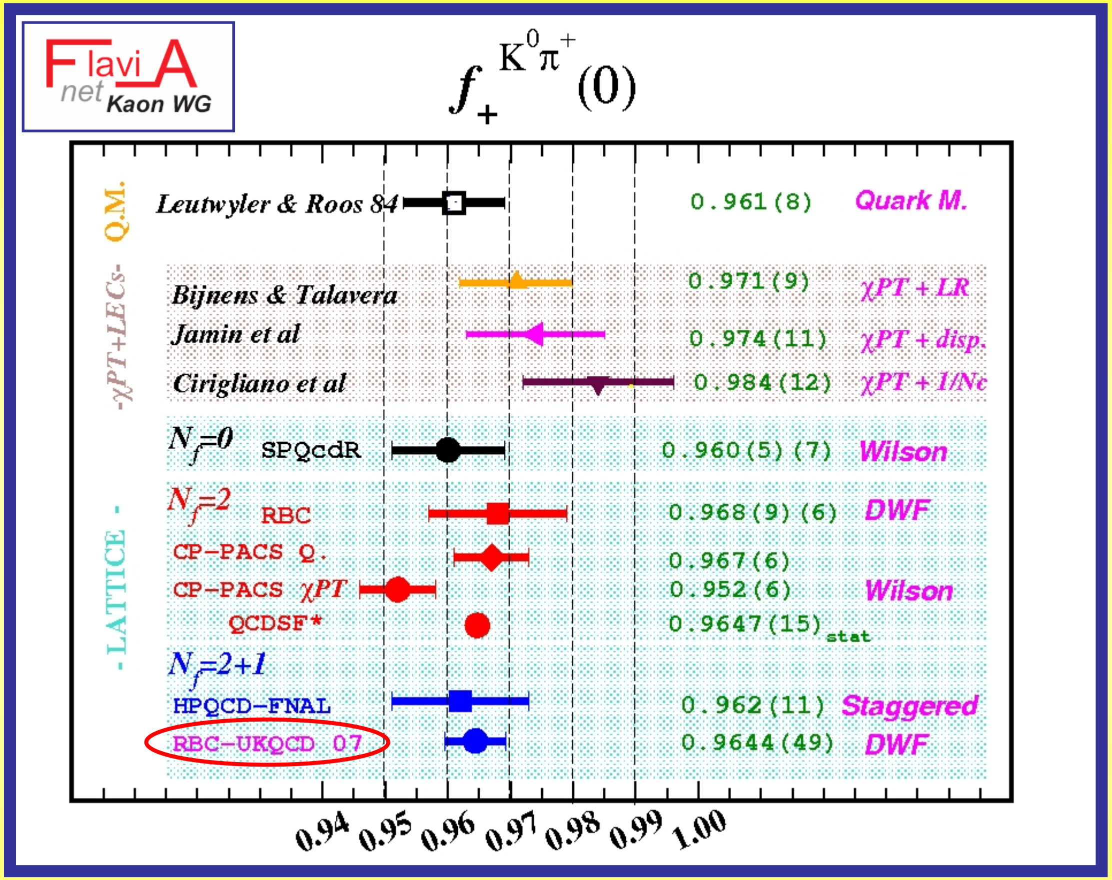
$$R = \frac{\langle \pi | \bar{s}\gamma_0 u | K \rangle \langle K | \bar{u}\gamma_0 s | \pi \rangle}{\langle \pi | \bar{u}\gamma_0 u | \pi \rangle \langle K | \bar{s}\gamma_0 s | K \rangle} = \frac{(M_K + M_\pi)^2}{4 M_K M_\pi} f_0(q^2_{max})^2$$







$f_+(0)$: LATTICE SUMMARY



- Good agreement between Nf=2 and 2+1 calculations and the first quenched result

- The error on $\Delta f = f_+(0)-1-f_2$ quoted in the original calculation was 50%

- A new precise Nf=2+1 calculation by RBC/UKQCD

-Analytical (model dependent) results slightly higher than Lattice QCD

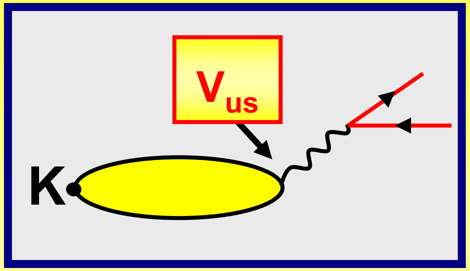
$f_+(0)=0.964(5) \rightarrow |V_{us}|=0.2246(12)$

A.Jüttner@Latt'07 & Flavianet Kaon WG

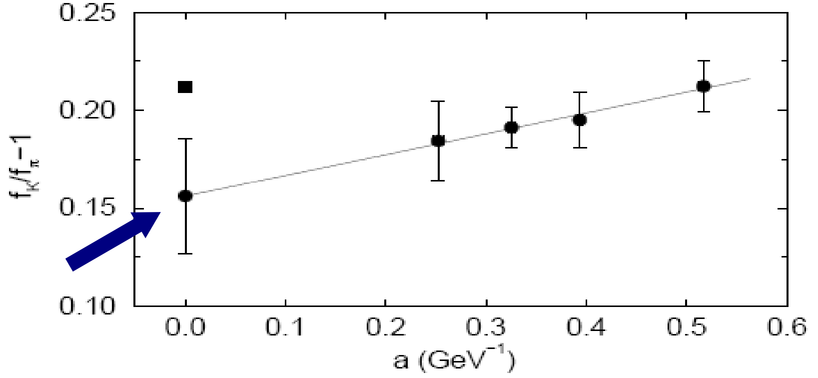
Vus/Vud from Kμ2/πμ2 decays

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

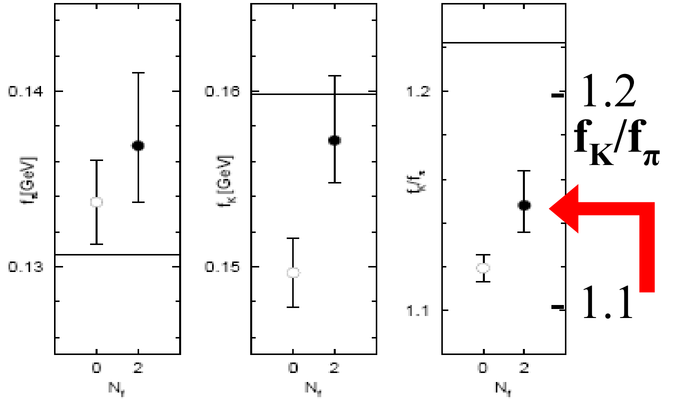
[Marciano 04]



Nf=0 CP-PACS 2000

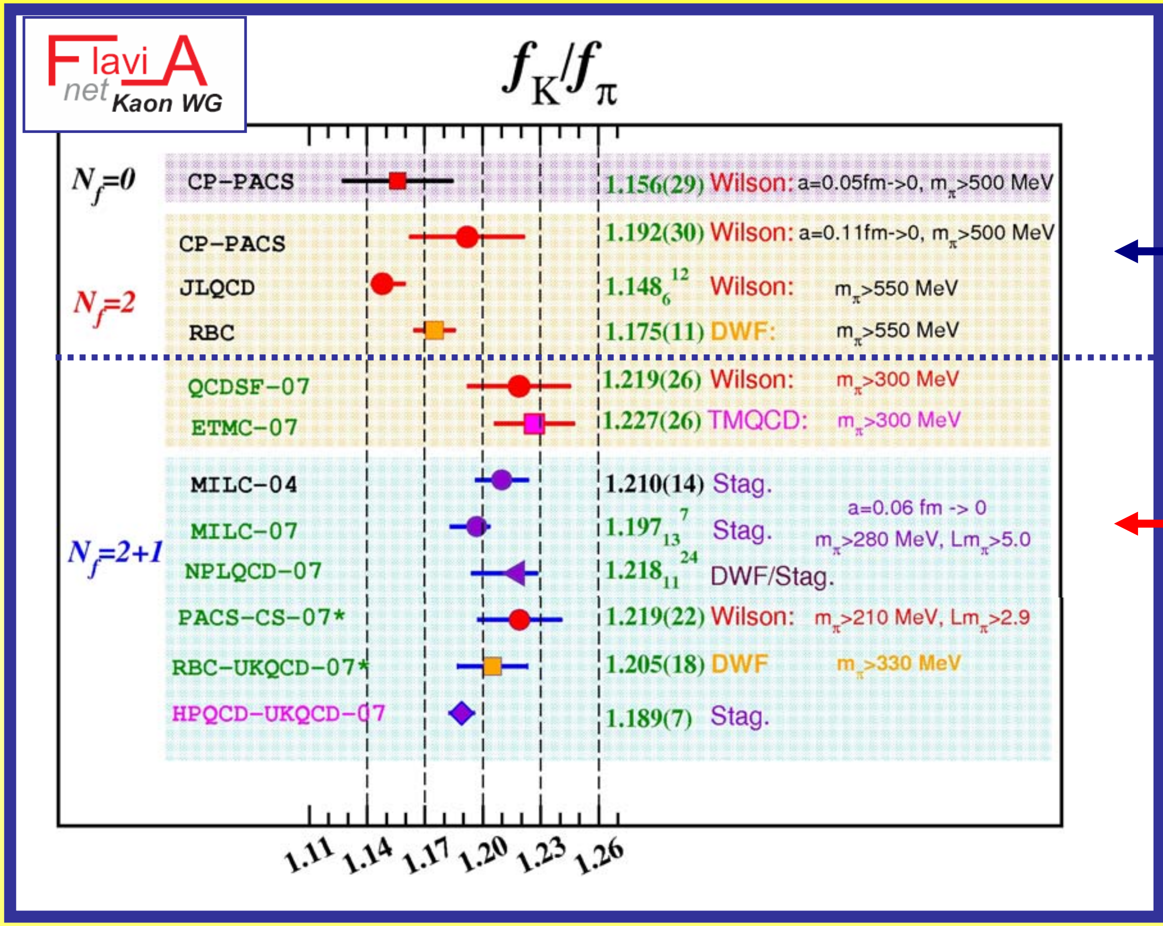


Nf=0,2 JLQCD 2002



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

fk/fπ: LATTICE SUMMARY



"Heavy" quark masses

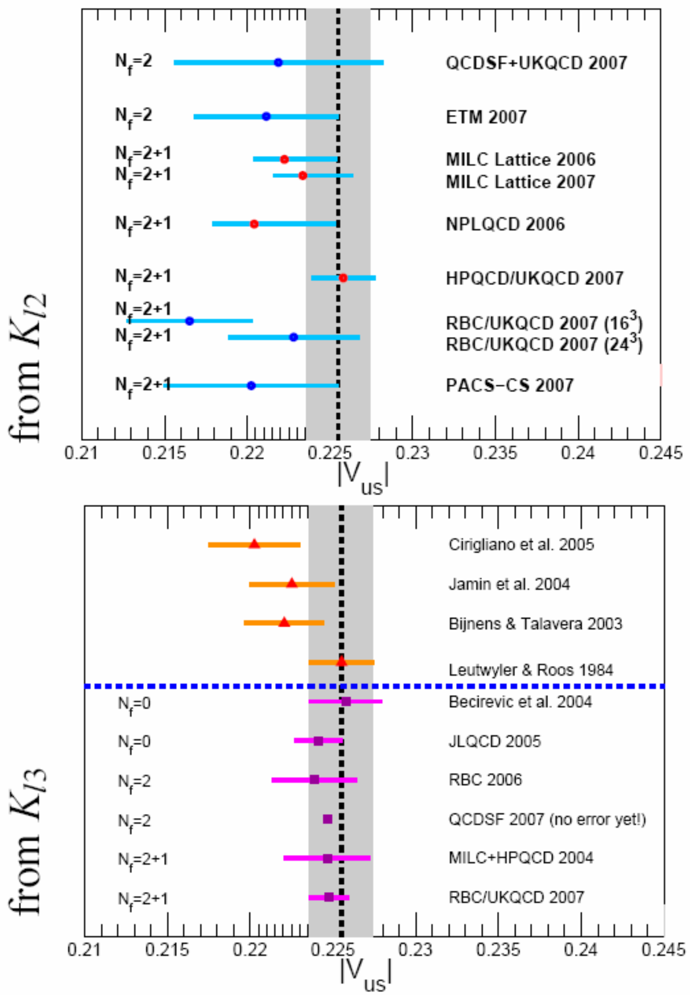
"Light" quark masses: many new results in the last year

f_K/f_π=1.198(10) ⟶ |Vus|=0.2241(24) A.Jüttner@Latt'07

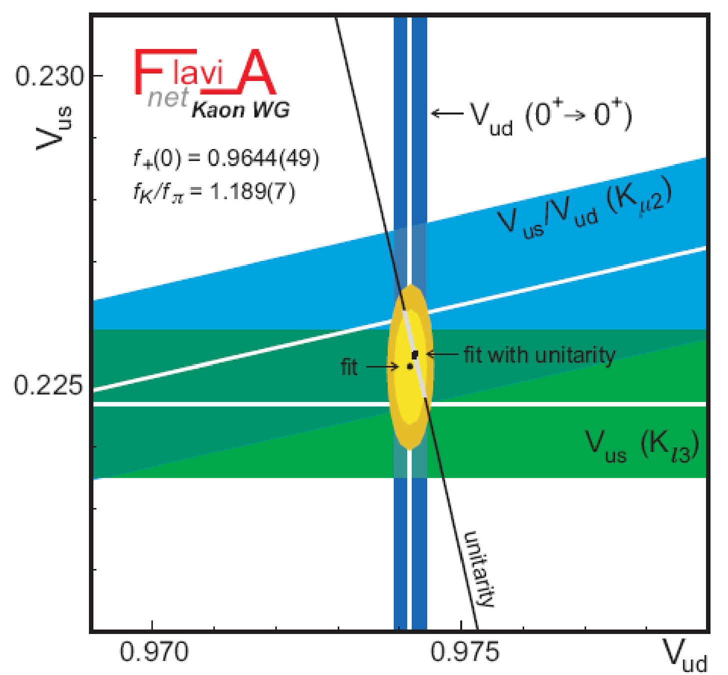
f_K/f_π=1.189(7) ⟶ |Vus|=0.2261(15) Flavianet Kaon WG

Vus SUMMARY

A.Jüttner, Latt'07



First row unitarity test



LATTICE QCD AND THE UNITARITY TRIANGLE ANALISYS

THE UNITARITY TRIANGLES

Unitarity relations:

(Bjorken-Jarlskog)

$$V^\dagger V = 1 \longrightarrow \sum_k V^*_{ki} V_{kj} = \delta_{ij}$$

9 constraints,

6 triangular relations

Only 2 triangles have all sides with length of the same $O(\lambda^3)$:

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

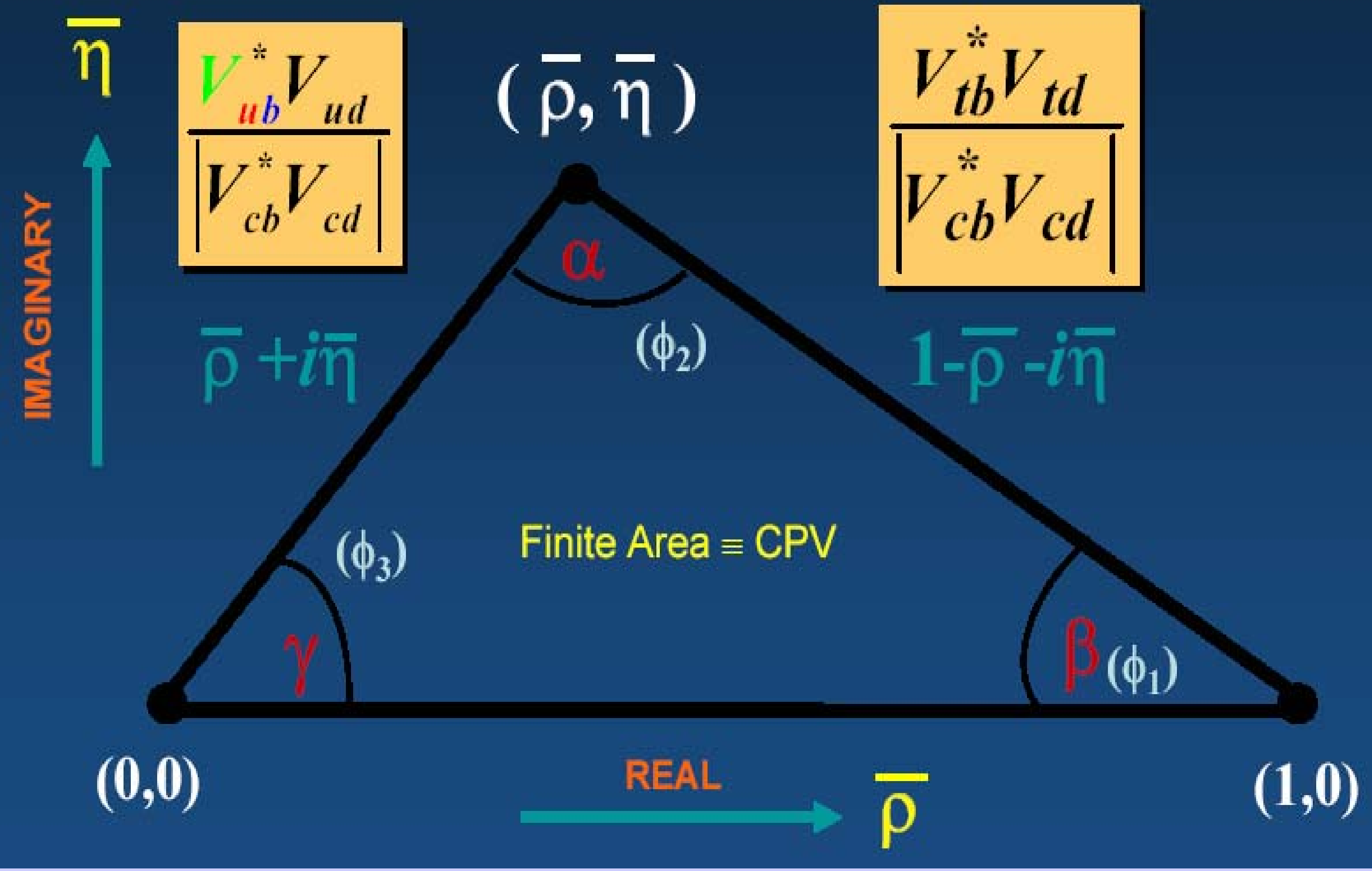
$$V_{ud} V^*_{td} + V_{us} V^*_{ts} + V_{ub} V^*_{tb} = 0$$

They are equivalent at order λ^3

Only the orientation of the triangles depends on the phase convention. The area and ~~CP~~ are proportional to:

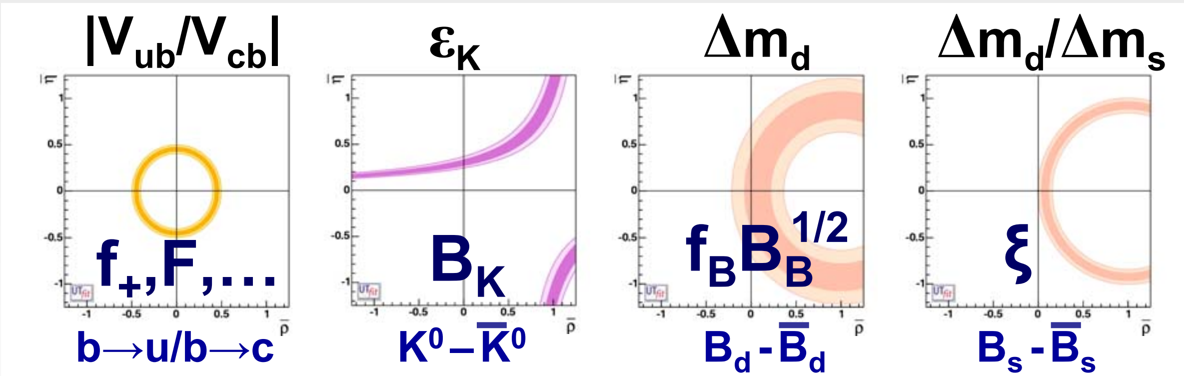
$$J = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23} \sin\delta \approx A^2 \lambda^6 \eta \sim 10^{-5}$$

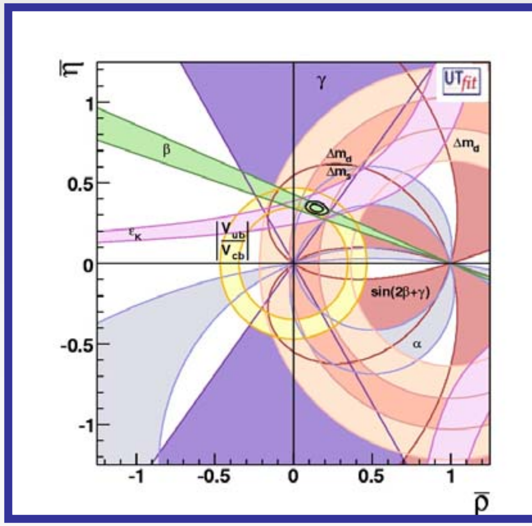
Unitarity: $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$



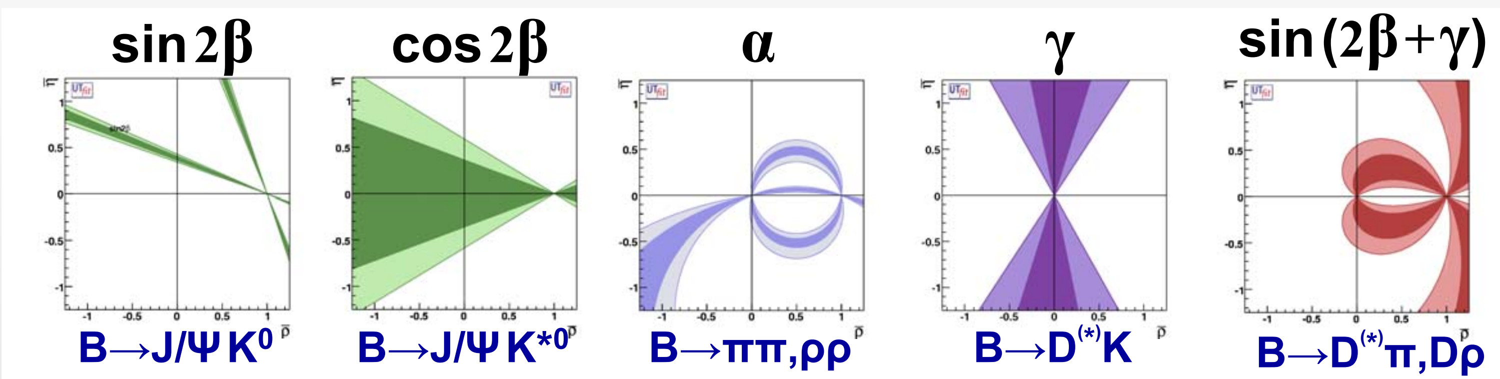
THE UTA CONSTRAINTS

UT-LATTICE

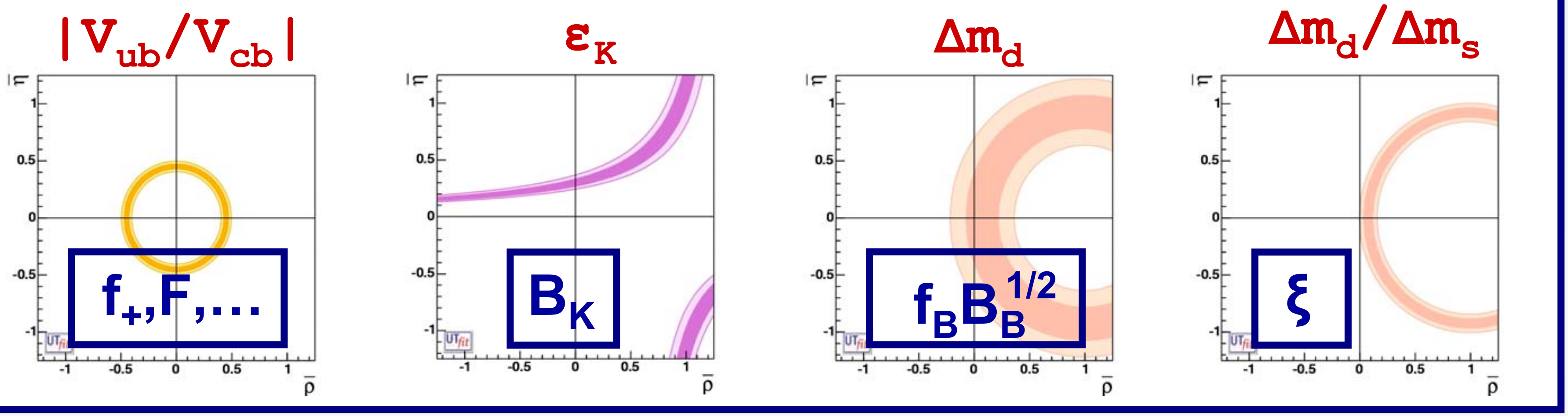




UT-ANGLES



THE "CLASSICAL" (pre-Bfactories) UT-LATTICE ANALYSIS



Hadronic matrix elements from LATTICE QCD

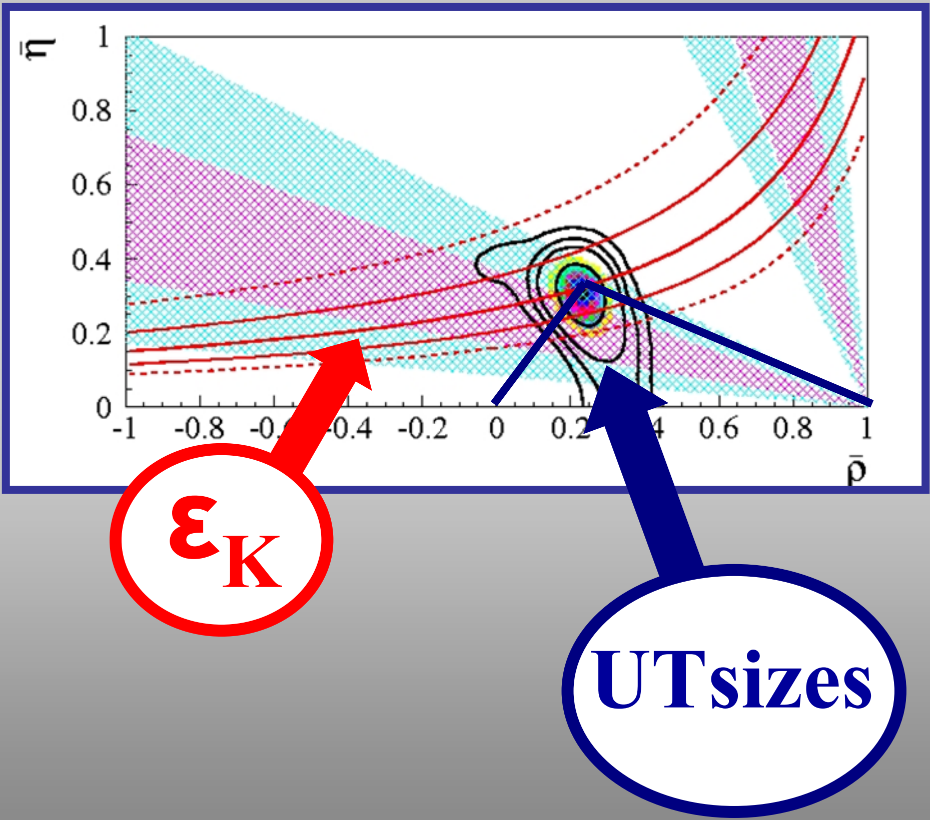
Already before the starting of the B factories

3 IMPORTANT RESULTS FOR FLAVOUR PHYSICS

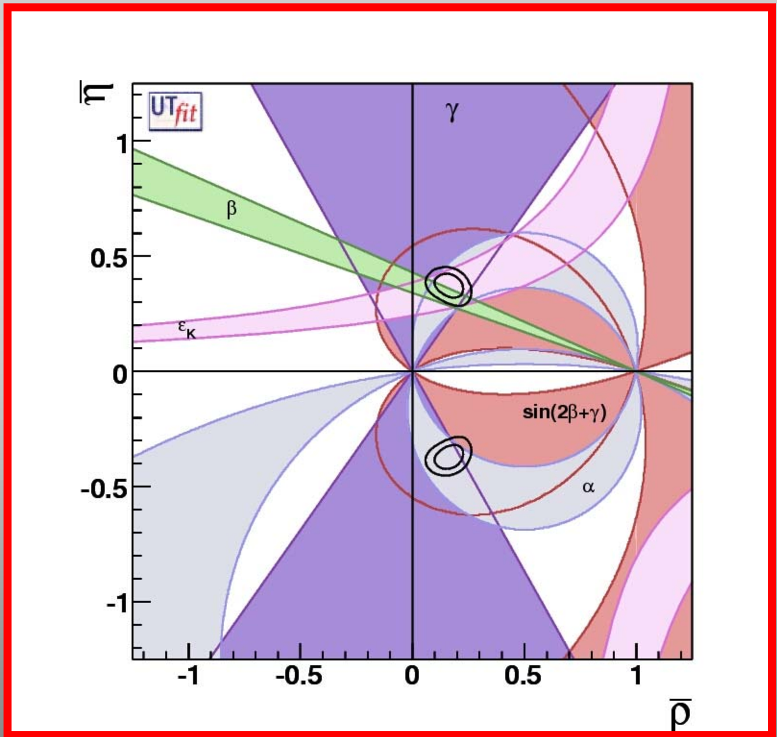
A success of (quenched) Lattice QCD calculations

1) CKM EXPLANATION OF ~~CP~~

Ciuchini et al.,2000



UTfit, today



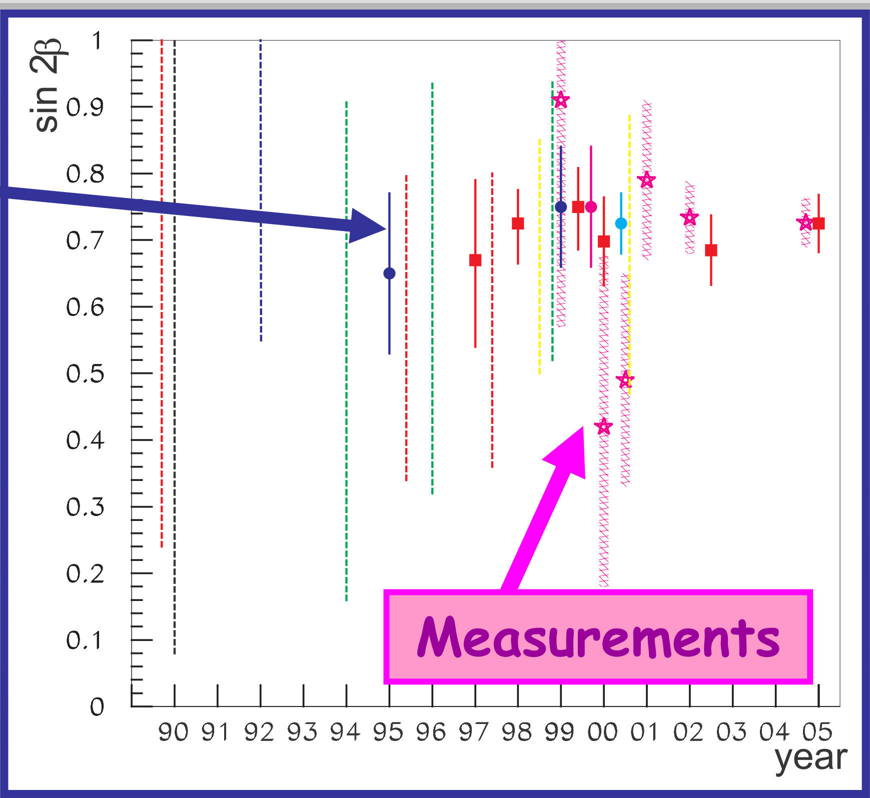
2) PREDICTION OF Sin2β

Ciuchini et al.,1995:
$Sin2\beta_{UTA} = 0.65 \pm 0.12$

Ciuchini et al.,2000:
$Sin2\beta_{UTA} = 0.698 \pm 0.066$

UTfit today:
$Sin2\beta_{UTA} = 0.744 \pm 0.039$

Predictions exist since 1995



Direct measurement today:
$Sin2\beta_{J/\psi\ K^{(*)}} = 0.681 \pm 0.025$

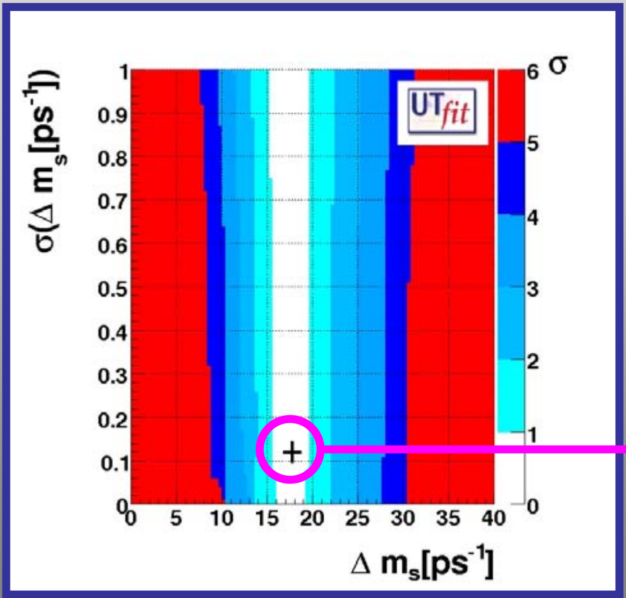
3) PREDICTION OF Δm_s

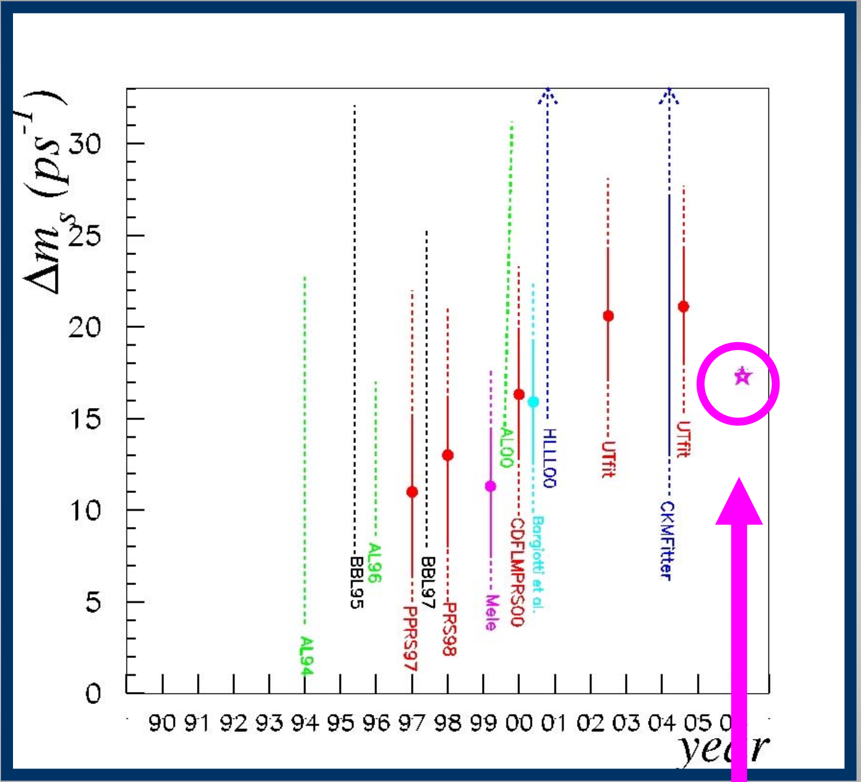
Ciuchini et al.,2000:

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

UTfit today:

$\Delta m_s = (18.6 \pm 2.3)\ ps^{-1}$



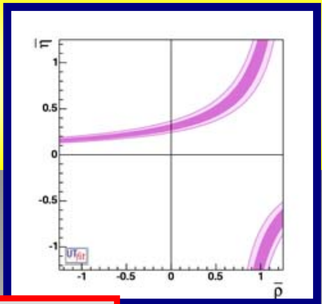


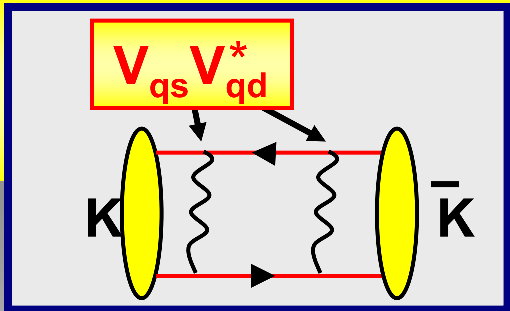
Direct measurement today

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

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

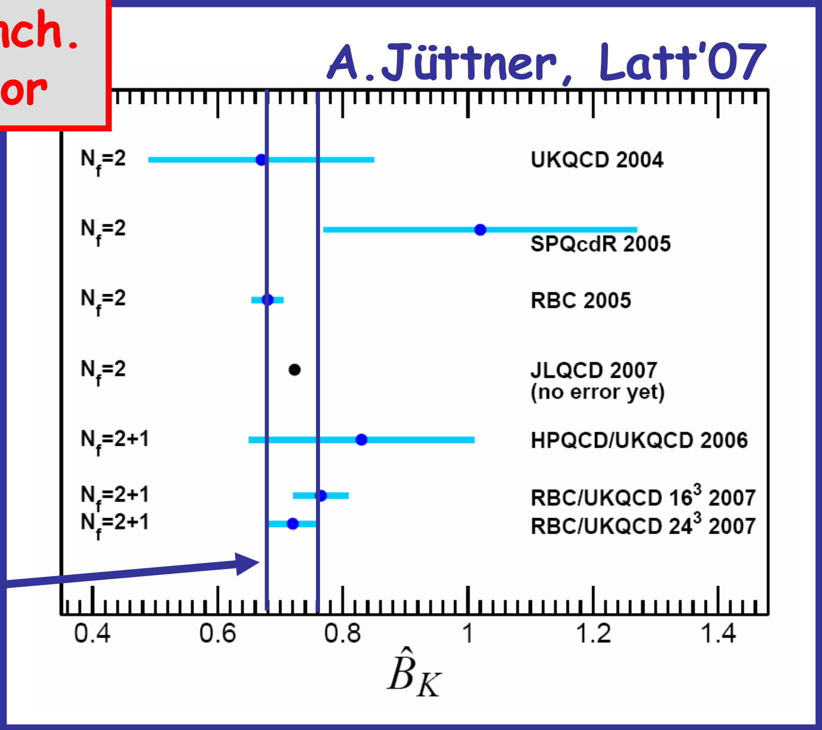
Quench. error

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

C.Dawson@Latt'05

$\hat{B}_K = 0.720 \pm 0.039$

A.Jüttner@Latt'07



Precise results from chiral fermions

CP-PACS, 0803.2569 [hep-lat]

A very precise quenched calculation

$\hat{B}_K = 0.782 \pm 0.005 \pm 0.007$

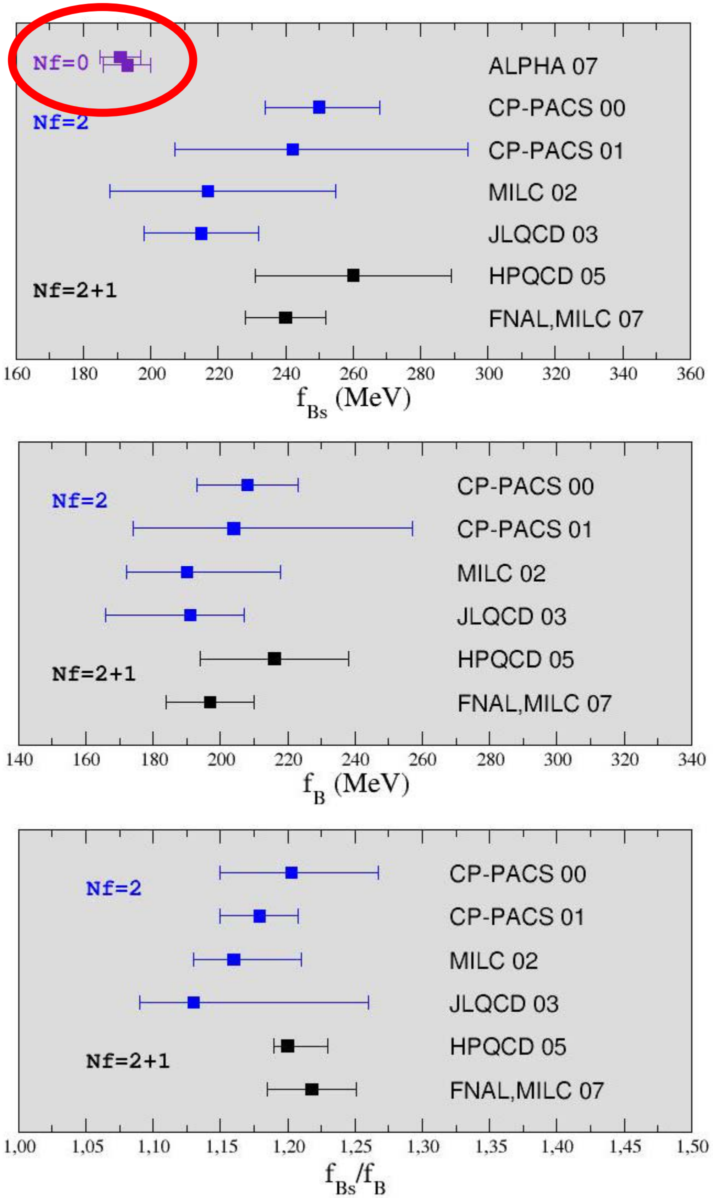
LQCD, Gavela et al., **1987**:

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

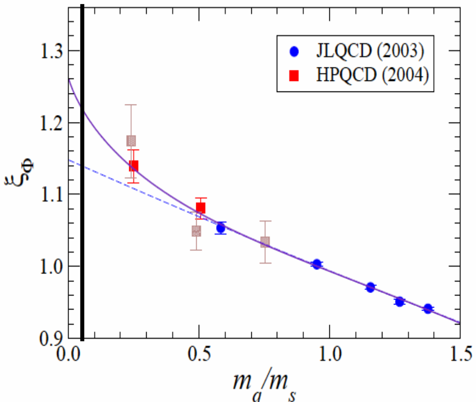
QCD SR, Pich, De Rafael, **1985**:

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

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



Inputs for $\Delta m_{d/s}$ and $B \to \tau\nu$



Chiral logs effects

Light m_q ($<m_s/2$) crucial for f_{Bs}/f_B

Kronfeld and Ryan, 2002:

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

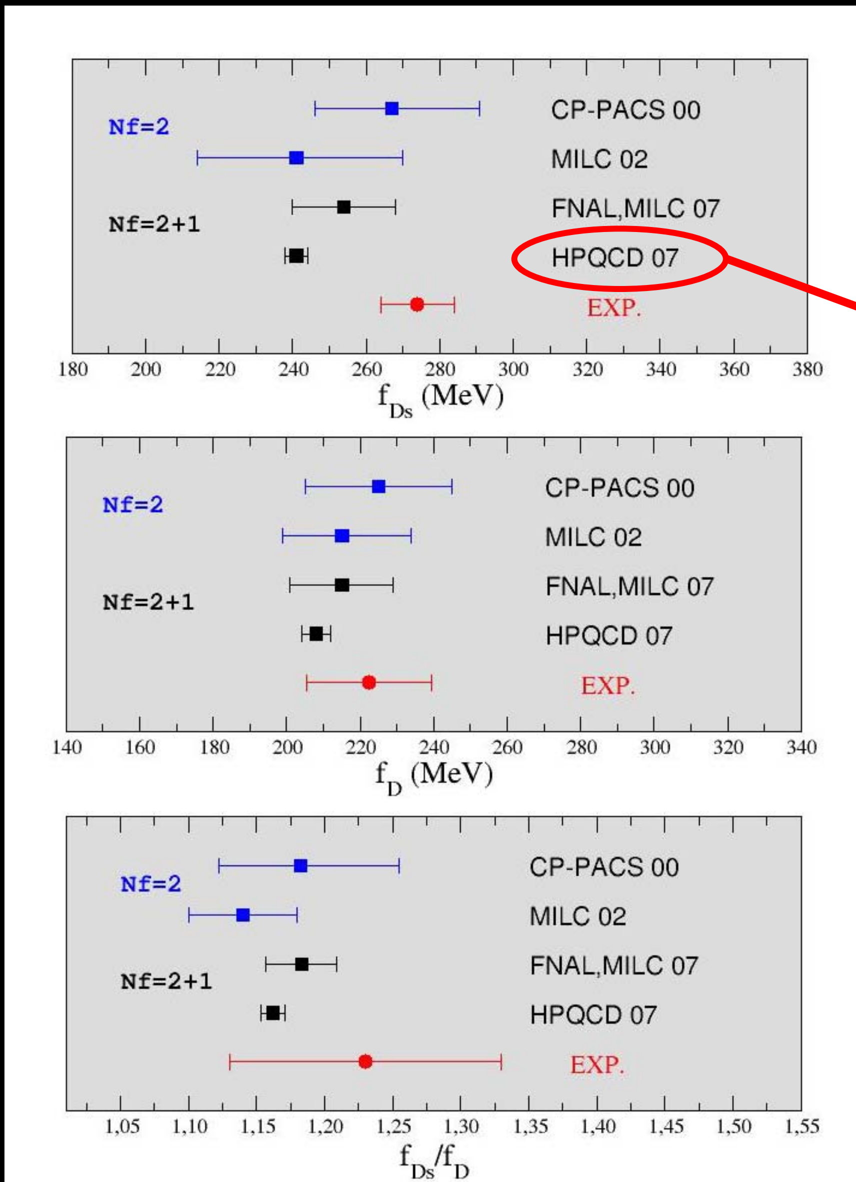
$f_{Bs} = 230 \pm 30$ MeV

$f_B = 189 \pm 27$ MeV

$f_{Bs}/f_B = 1.23 \pm 0.06$

Averages used in the UT fit

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



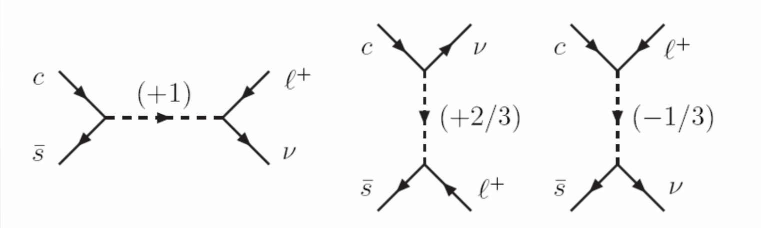
"CLEO-c has the potential to provide a unique and crucial validation of LQCD"

Ian Shipsey @ FPCP 2002

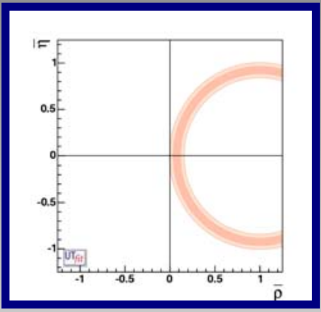
Co-Spokesperson of the CLEO Collaboration

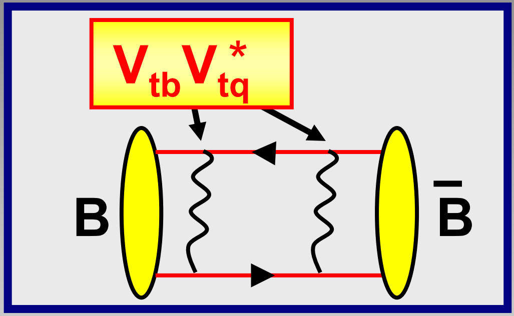
A new result by HPQCD, which claims a 1.2% precision on fDs, shows a discrepancy of about 3.5-4.0 σ with the experimental average.

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

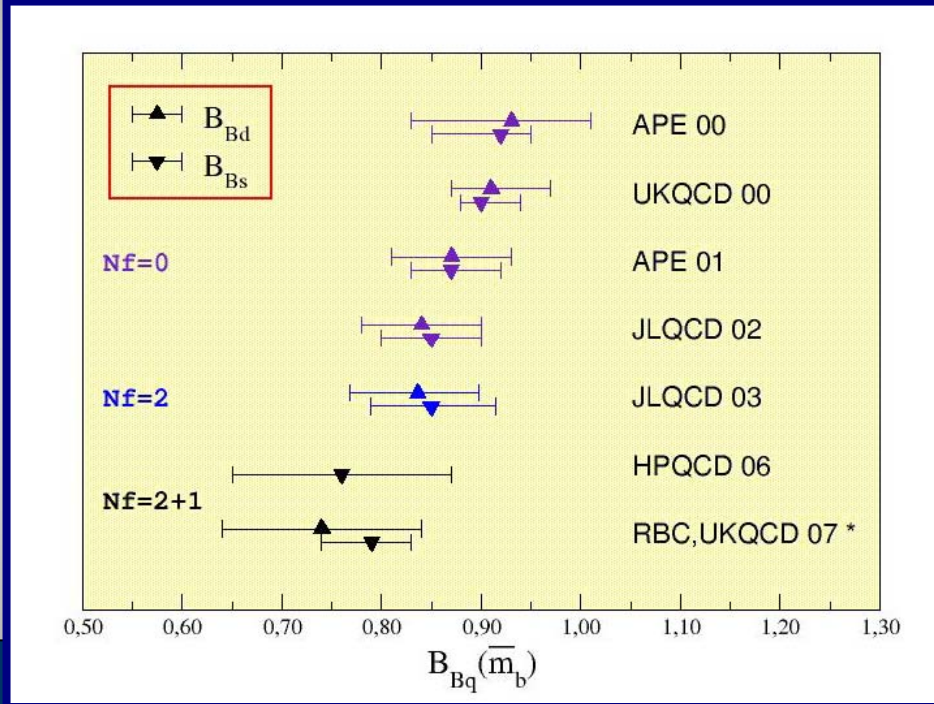


B-$\bar{B}$ mixing: B_{Bd} and B_{Bs}





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



- Small chiral logs effects: $B_{Bd} \approx B_{Bs}$
- Small quenching effects: consistent Nf=0, Nf=2 and Nf=2+1 results

Averages used in the UT fit

$f_{Bs}\sqrt{\hat{B}_{Bs}}$ = 262 ± 35 MeV

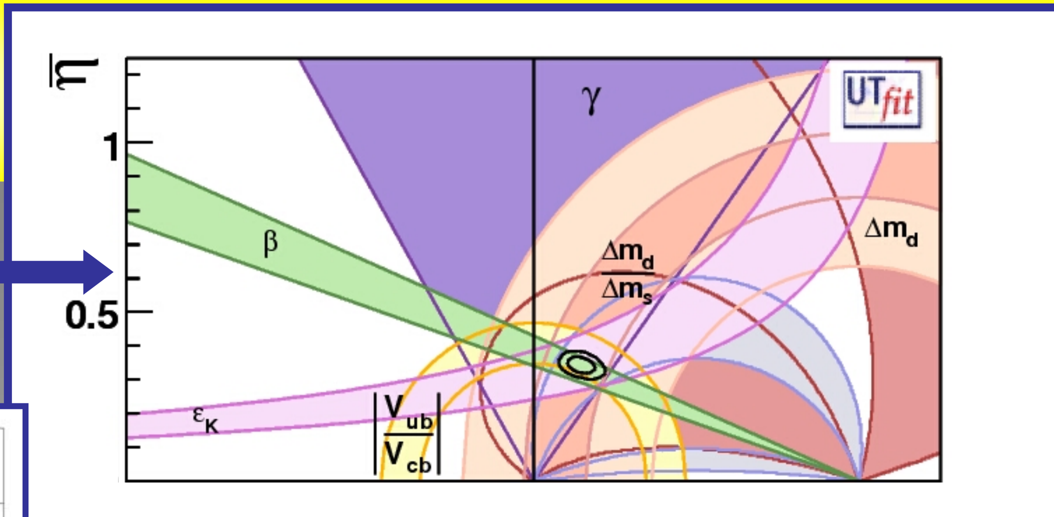
ξ = 1.23 ± 0.06

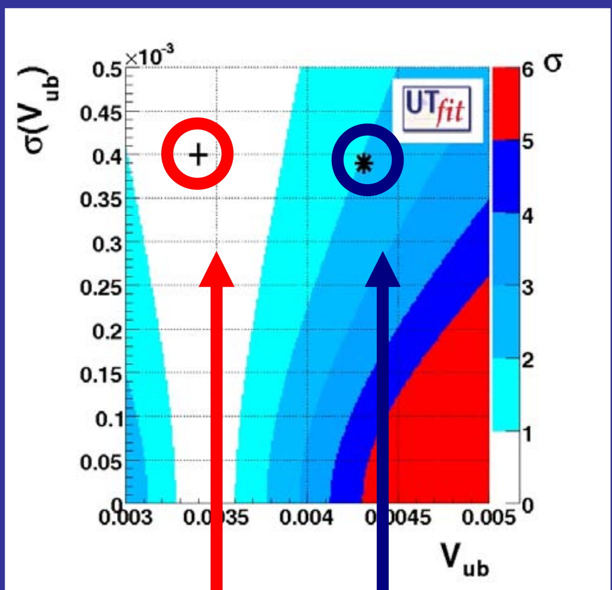
$B_{Bd}(\bar{m}_b) = B_{Bs}(\bar{m}_b)$ =

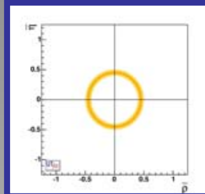
0.84 ± 0.03 ± 0.06

Vub from B→πlν

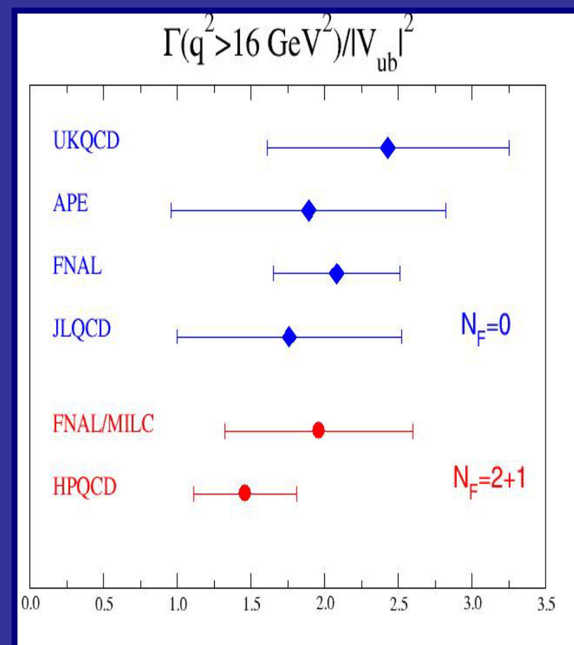
Tension between V_{ub} inclusive and the UT fit







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

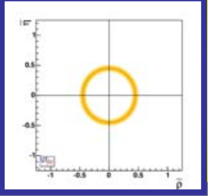


EXCLUSIVE: $V_{ub}^{excl.} = (34.0 \pm 4.0)\ 10^{-4}$

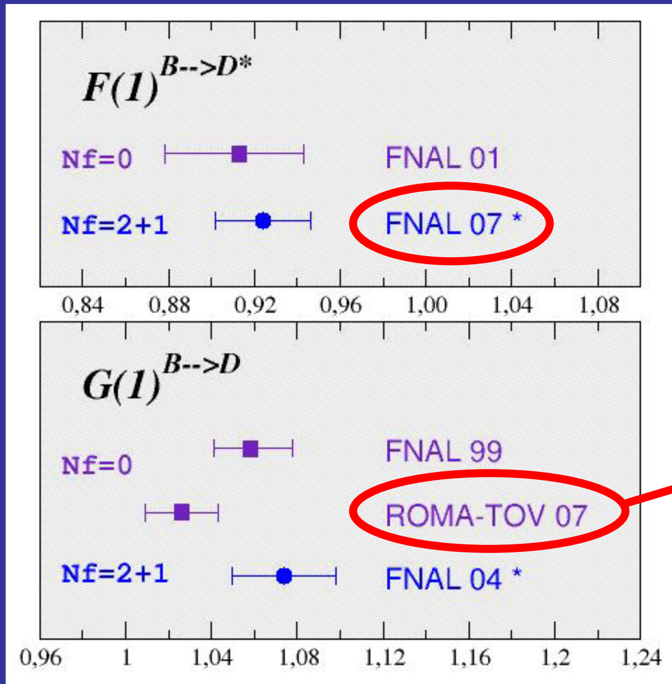
Form factors from LQCD and QCDSR

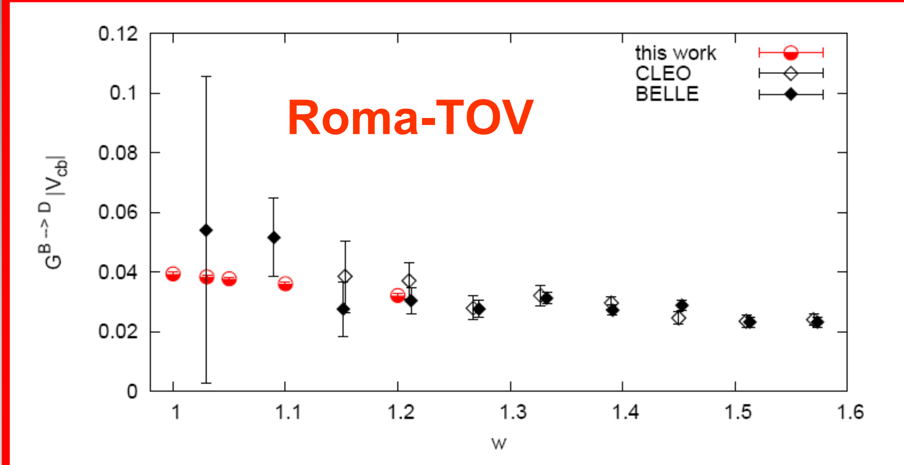
INCLUSIVE: $V_{ub}^{incl.} = (43.1 \pm 3.9)\ 10^{-4}$

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

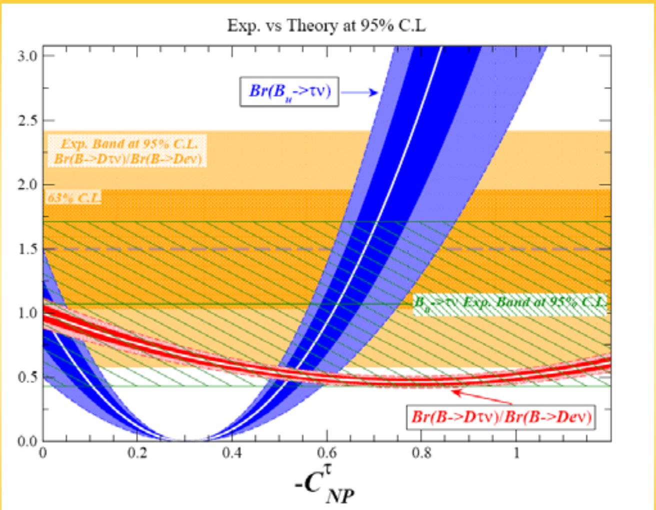


Vcb from B→D/D*lν decays





Kamenik and Mescia, `0802.3790[hep-ph]`



Charged Higgs contribution to the scalar amplitude in B→Dτν

Two new results

-FNAL: B→D*, Nf=2+1

-Roma TOV: B→D, Nf=0:
New method (Step Scaling Method +Twisted b.c.), w≥1, both vector and scalar ff's.

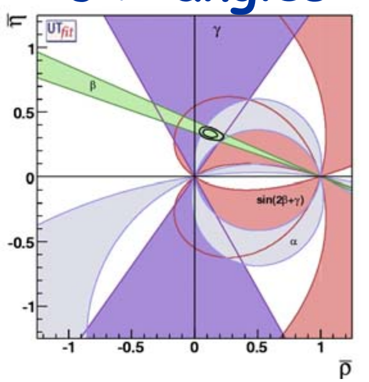
“EXPERIMENTAL” DETERMINATION OF LATTICE PARAMETERS

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

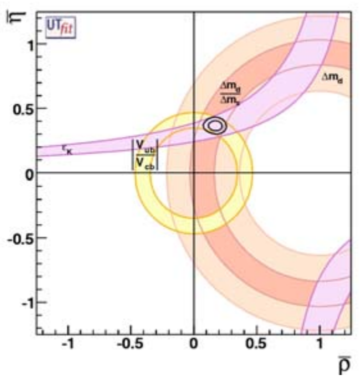
$$|\varepsilon_K| = C_\varepsilon A^2\lambda^6\,\bar{\eta}\left[-\eta_1 S(x_c) + \eta_2 S(x_t)\left(A^2\lambda^4(1-\bar{\rho})\right) + \eta_3 S(x_c, x_t)\right]\hat{B}_K$$

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

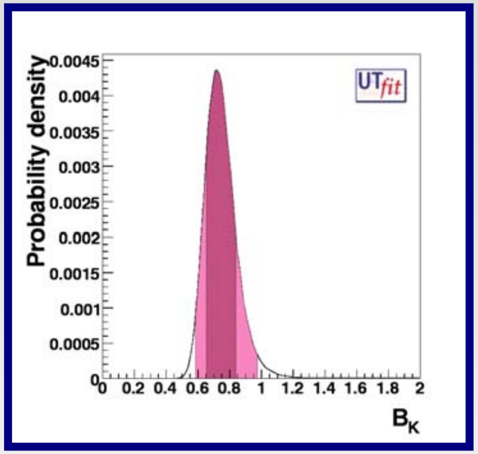
UT-angles

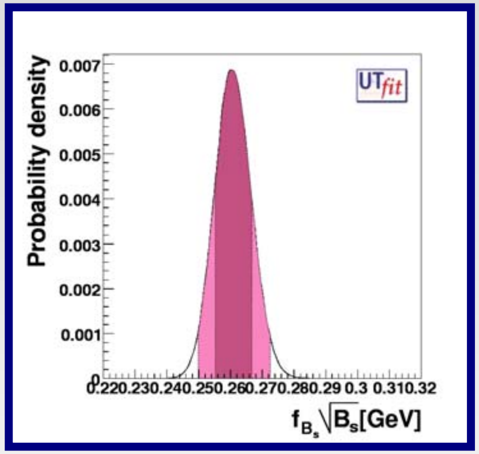


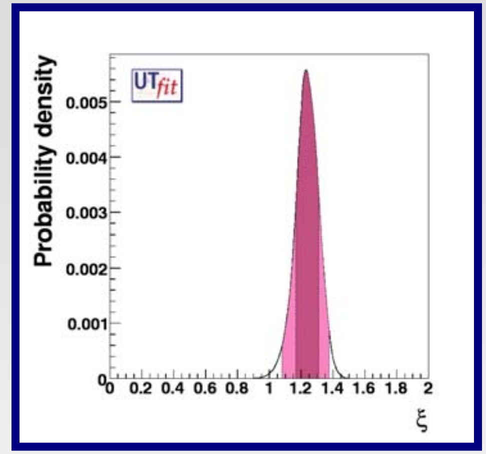
UT-lattice



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







2%! from Δm_s

	B_K	$f_{B_s}\sqrt{B_{B_s}}$ (MeV)	ξ
UTA	0.75 ± 0.09	261 ± 6	1.24 ± 0.08
Lattice	0.79 ± 0.04 ± 0.08	262 ± 35	1.23 ± 0.06
Recent results	0.720 ± 0.039 RBC/UKQCD 07	281 ± 21 HPQCD 06	1.21 ± 0.03 HPQCD,FNAL/MILC 07

Very good agreement. Increasing precision of LQCD.
The role of LQCD in the SM UTA is not crucial…

… but Lattice QCD calculations are essential to perform

THE UTA BEYOND THE STANDARD MODEL

THE UTA BEYOND THE SM: A MODEL INDEPENDENT ANALYSIS

New Physics in $\Delta F = 2$ amplitudes can be parameterized in a simple general form. For instance:

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

6 additional free parameters

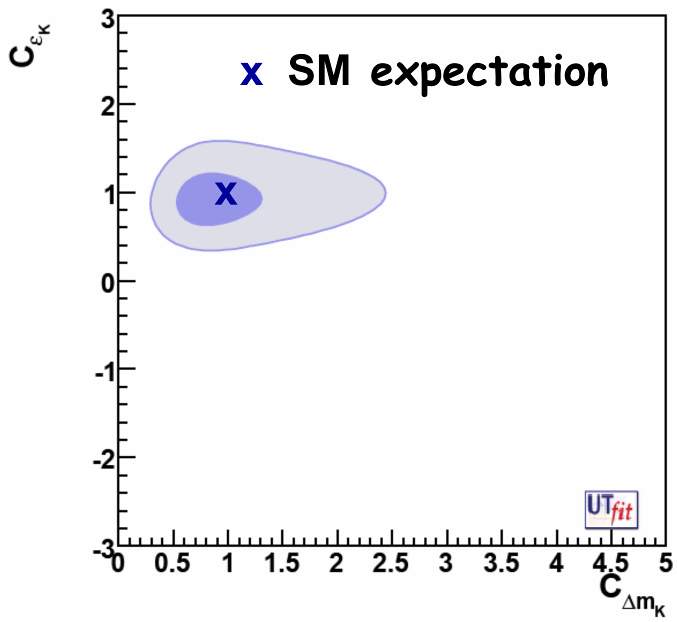
$C_{Bd}, \varphi_{Bd}, C_{Bs}, \varphi_{Bs}, C_{\varepsilon K}, C_{\Delta mK}$

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

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

A number of additional constraints are included: semileptonic asymmetries (A_{SL}^d, A_{SL}^s), dimuon charge asymmetry ($A_{SL}^{\mu\mu}$), lifetime differences and mixing phases ($\Delta\Gamma_d/\Gamma_d$, $\Delta\Gamma_s/\Gamma_s$, ϕ_s)

K-K mixing

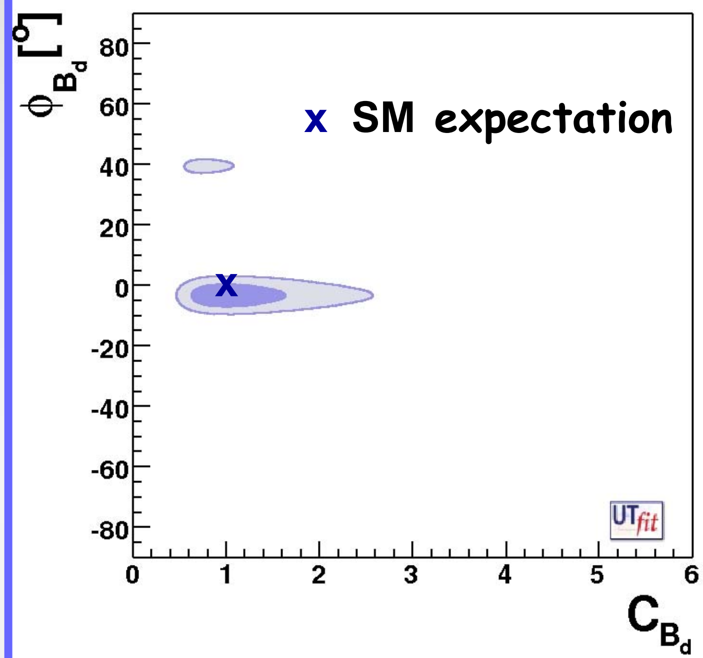


$C_{\Delta mK} = 0.93 \pm 0.32$

$C_{\varepsilon K} = 0.92 \pm 0.14$

UTfit 0707.0636 [hep-ph]

B_d-B_d mixing



$C_{Bd} = 1.05 \pm 0.34$

$\varphi_{Bd} = (-3.4 \pm 2.2)^{o}$

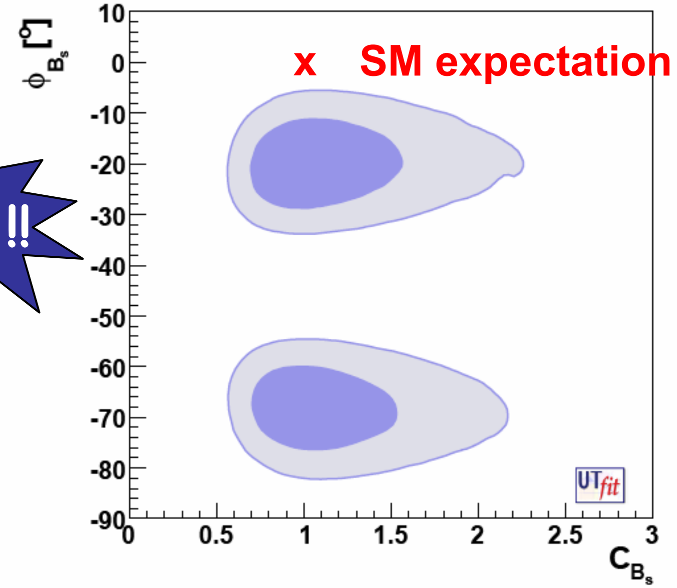
The Vub tension produces a 1.5σ effect in φ_{Bd}

EVIDENCE OF NEW PHYSICS IN Bs MIXING

$\Delta\Gamma$ and φ_{Bs} from the time-dependent angular analysis of $B_s \to J/\Psi\ \Phi$

NEW !!

UTfit 0803.0659 [hep-ph]



$C_{Bs} = 1.07 \pm 0.29$

$\varphi_{Bs} = (-19.9 \pm 5.6)^o \cup (-68.2 \pm 4.9)^o$

$(\Delta m_s)^{exp} = C_{Bs}\,(\Delta m_s)^{SM}$

$\sin 2\beta_s^{exp} = \sin 2(\beta_s^{SM} + \varphi_{Bs})$

The accuracy on $f_{Bs}\sqrt{B_{Bs}}$ required to observe NP in Δm_s at 3σ is:

	1.7%	3.3%	5.0%
for C_{Bs}	1.1	1.2	1.3

The present accuracy is ~7-10%

LATTICE QCD AND QUARK MASSES

♦ QUARK MASSES CANNOT BE DIRECTLY MEASURED IN THE EXPERIMENTS, BECAUSE QUARKS ARE CONFINED INSIDE HADRONS

♦ BEING FUNDAMENTAL PARAMETERS OF THE STANDARD MODEL, QUARK MASSES CANNOT BE DETERMINED BY THEORETICAL CONSIDERATIONS ONLY.

➡ QUARK MASSES CAN BE DETERMINED BY COMBINING TOGETHER A THEORETICAL AND AN EXPERIMENTAL INPUT. E.G.:

$$[M_{HAD}(\Lambda_{QCD}, m_q)]^{TH.} = [M_{HAD}]^{EXP.}$$

LATTICE QCD

LATTICE DETERMINATION OF QUARK MASSES

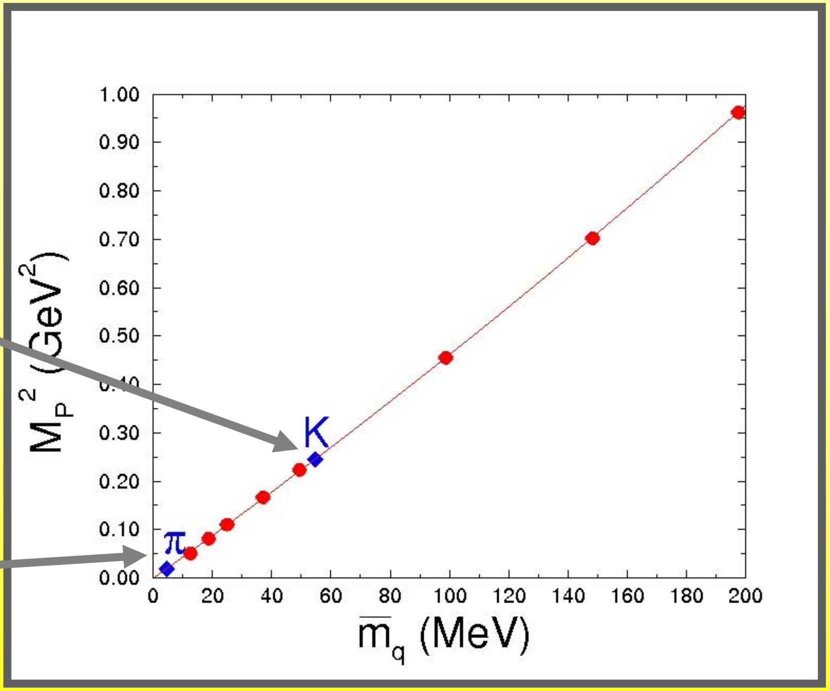
$$\hat{m}_q(\mu) = m_q(a)\, Z_m(\mu a)$$

ADJUSTED UNTIL
$M_H^{LATT} = M_H^{EXP}$

PERTURBATION THEORY OR
NON-PERTURBATIVE METHODS

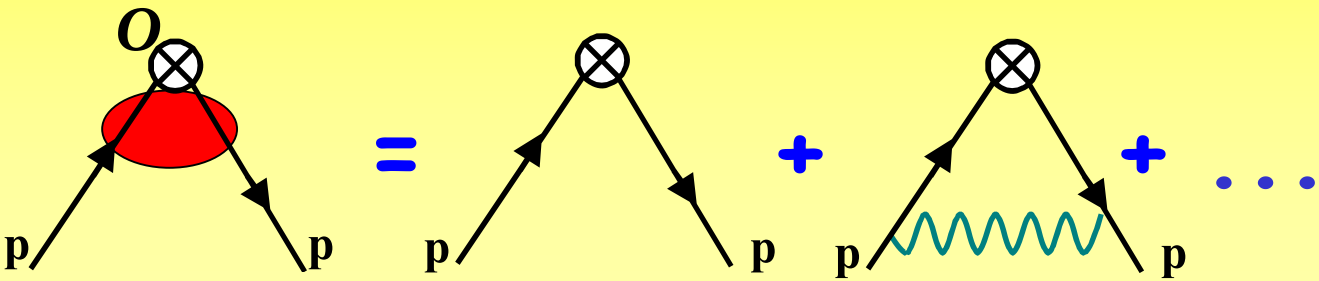
Extrapolation to $m_q = m_s$

Extrapolation to $m_q = m_{u,d}$



The effect of non-perturbative renormalization can be as large as 50%

NON-PERTURBATIVE RENORMALIZATION
THE RI-MOM METHOD

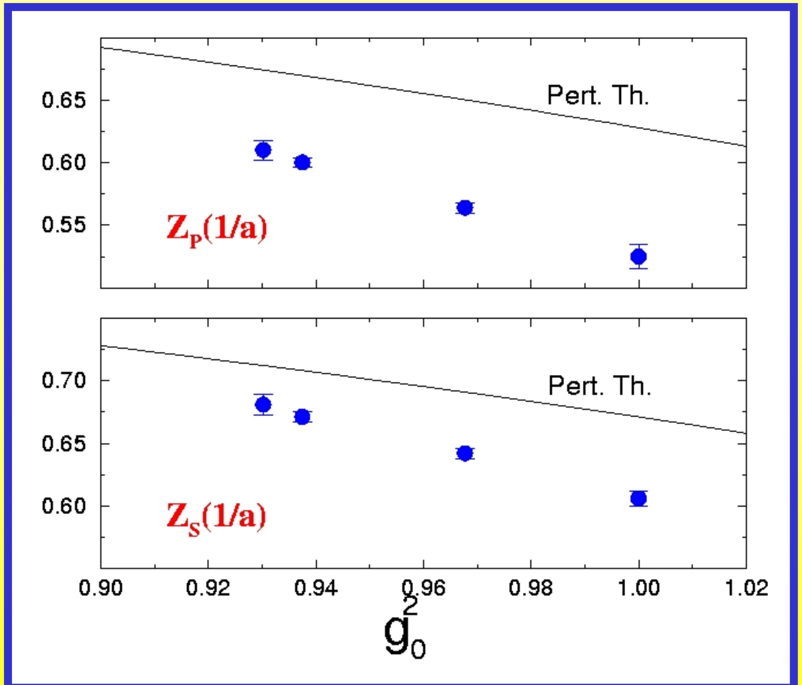


$\Gamma_O(p^2)$

The (non-perturbative) renormalization condition:

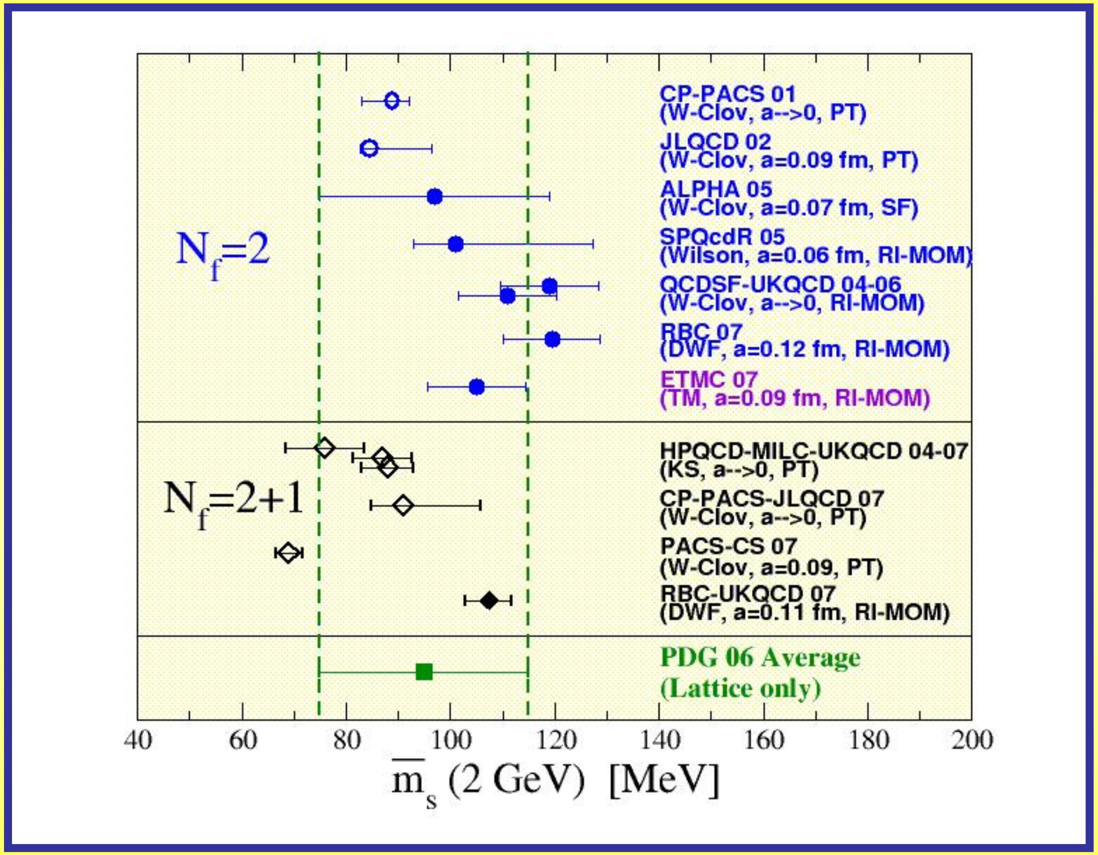
$$Z_O(a\mu)\,\Gamma_O(p^2)|_{p^2=\mu^2} = \Gamma_{\text{Tree-Level}}$$

Several NPR techniques have been developed: Ward Identities, Schrodinger functional, X-space



ms: LATTICE SUMMARY

from ETM Collaboration, 0710.0329 [hep-lat]



(*) Empty symbols: perturbative renormalization

CP-PACS, 0803.2569 [hep-lat]

A very <u>"precise" quenched calculation</u>

$$m_s^{MS}(2\ \text{GeV}) = 105.6\ (1.2)\ \text{MeV}$$

The same accuracy can be reached in unquenched determinations

The error introduced by the use of perturbative renormalization is typically larger than other systematic effects, including quenching

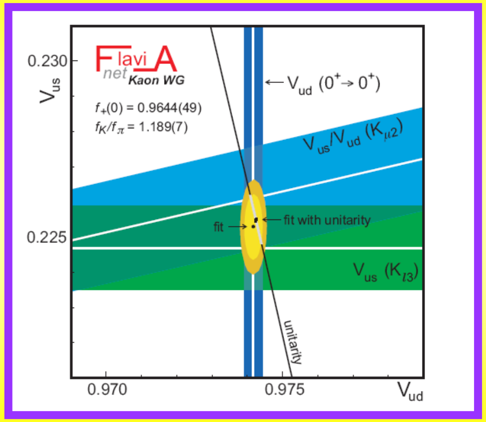
LATTICE QCD AND FLAVOUR PHYSICS

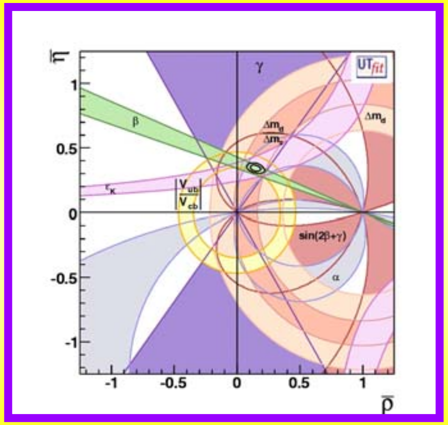
The past

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

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

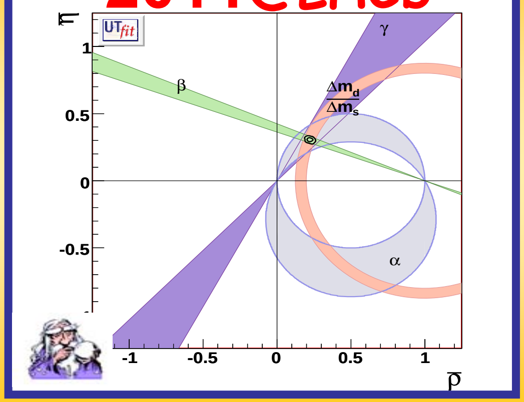
the present



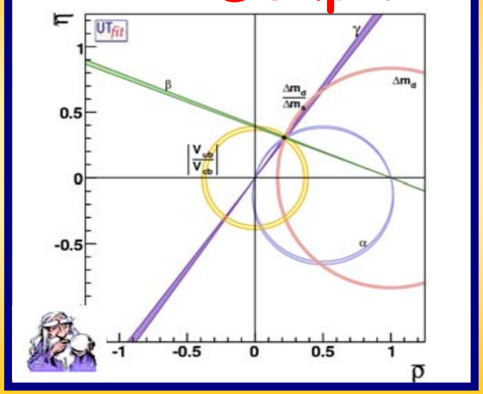


and the future

2011@LHCb



2015@SuperB



1. FLAVOUR PHYSICS AND ITS MOTIVATIONS

- Introduction to Flavour Physics
- Evidence of physics beyond the Standard Model
- Flavour physics as a probe of New Physics

2. FLAVOUR PHYSICS AND LATTICE QCD

- The "precision era" of Lattice QCD (why now)
- Vus and the first row unitarity test
- Lattice QCD and the Unitarity Triangle Analysis
- The UTA beyond the Standard Model: evidence of New Physics in Bs mixing NEW !!
- Lattice QCD and quark masses

Appendix: a simple model of Flavour Physics

THE QUARK MASS MATRICES

$$\mathrm{L}^{Yukawa} = - \sum_{i,k} [\overline{Q}^i_L Y^d_{ik} D^k_R H + \overline{Q}^i_L Y^u_{ik} U^k_R H^C] + + \text{h.c.}$$

Gauge symmetry breaking

$$\mathrm{L}^{mass} = - \sum_{i,k} [\overline{d}^i_L m^d_{ik} d^k_R + \overline{u}^i_L m^u_{ik} u^k_R] + \text{h.c.}$$

$$m^q = Y^q v / \sqrt{2}$$

$\longleftrightarrow$ $M_W = gv/2$

Why $m^q \neq O(M_W)$??

DIAGONALIZATION OF THE MASS MATRIX

The mass matrices m^q are not Hermitean. Up to singular cases, they can be diagonalized by 2 unitary transformations:

$$U_L^\dagger m U_R = m_D$$

$$\begin{cases} U_L^\dagger m m^\dagger U_L = m_D m_D^\dagger \\ U_R^\dagger m^\dagger m U_R = m_D^\dagger m_D \end{cases}$$

i

$$(U_L^\dagger)_{ik} q_L^k \rightarrow q_L^i \ , \ (U_R^\dagger)_{ik} q_R^k \rightarrow q_R^i$$

($U_{L,R}$ different for u^k and d^k)

$$L^{mass} = -[m_u \bar{u}_L u_R + m_d \bar{d}_L d_R + \ldots] + h.c.$$

With respect to:

$$(U_L^\dagger)_{ik}\, q_L^k \rightarrow q_L^i \;,\; (U_R^\dagger)_{ik}\, q_R^k \rightarrow q_R^i$$

neutral currents $\bar{q}_L^i \gamma_\mu q_L^i$ and $\bar{q}_R^i \gamma_\mu q_R^i$ are invariant: quark kinetic terms, QCD couplings with gluons, QED couplings with photons, weak couplings with Z^0

No flavor changing neutral currents (FCNC) at tree level

The only effect is in the weak charged currents:

$$\bar{u}_L^i \gamma_\mu d_L^i \cdot W^\mu \rightarrow \bar{u}_L^k \gamma_\mu (U_L^{u\dagger} U_L^d)_{kj}\, d_L^j \cdot W^\mu$$

$$V_{CKM} = U_L^{u\dagger} U_L^d$$

$$V_{CKM} V_{CKM}^\dagger = 1$$

THERE IS A CLEAR CORRELATION BETWEEN MASSES AND MIXINGS ANGLES

In the first 2 generations:

$$\left(\frac{m_d}{m_s}\right)^{1/2} \approx 0.24 \qquad \left(\frac{m_u}{m_c}\right)^{1/4} \approx 0.22$$

$$\Rightarrow \quad \left(\frac{m_d}{m_s}\right)^{1/2} \approx \left(\frac{m_u}{m_c}\right)^{1/4} \approx V_{us}$$

Can we explain this relation ?

MASS TEXTURES

Two generations:

Gatto et al.

$$\mathbf{m^d} = m_s \begin{pmatrix} 0 & -\sqrt{x} \\ \sqrt{x} & 1+x \end{pmatrix} \qquad \mathbf{m^u} = \begin{pmatrix} m_u & 0 \\ 0 & m_c \end{pmatrix}$$

$$\mathrm{diag}(\mathbf{m^d}) = m_s(x, 1) \Longrightarrow x = m_d / m_s$$

Diagonalization:

$$\begin{cases} U_L^\dagger \mathbf{m}\,\mathbf{m}^\dagger U_L = \mathbf{m}_D \mathbf{m}_D^\dagger & U_L^\dagger \mathbf{m}\, U_R = \mathbf{m}_D \\ U_R^\dagger \mathbf{m}^\dagger \mathbf{m}\, U_R = \mathbf{m}_D^\dagger \mathbf{m}_D & V_{CKM} = U_L^{u\dagger} U_L^d \end{cases}$$

$$V_{CKM} = U_L^{u\dagger} U_L^d = U_L^d \approx \begin{pmatrix} 1 - x/2 & \sqrt{x} \\ -\sqrt{x} & 1 - x/2 \end{pmatrix}$$

$$V_{us} = \sin\theta_C = \sqrt{x} = \sqrt{m_d/m_s} \approx 0.22$$

Which theory of flavor generates this texture?

HORIZONTAL SYMMETRIES

Example: **Horizontal U(2)** (Barbieri, Hall, ...)

$q^a \to U_{ab}\, q^b \quad , \quad U \in U(2)$ $\quad a,b = 1,2$ (Generation indices)

$$L = \frac{1}{M_F}\,\phi_{ab}\, q^a\, q^b\, H$$

Non-renorm. interaction

M_F = flavor scale

"Flavon" field — ϕ_{ab}

Higgs field (U(2) scalar) — H

$$\phi_{ab} = S_{ab} + A_{ab}$$

S_{ab}: Symmetric tensor

A_{ab}: Anti-symmetric tensor

$$U(2) \xrightarrow{S_{ab}} U(1) \xrightarrow{A_{ab}} \{1\}$$

$$\langle S_{ab} \rangle = \begin{pmatrix} 0 & 0 \\ 0 & V \end{pmatrix} \qquad \langle A_{ab} \rangle = \begin{pmatrix} 0 & -v \\ v & 0 \end{pmatrix}$$

$$L = \frac{1}{M_F} (S_{ab} + A_{ab})\, q^a q^b H$$ → **Flavor symm. breaking**

$$\rightarrow \frac{V}{M_F} q^2 q^2 H + \frac{v}{M_F} (q^2 q^1 - q^1 q^2) H \equiv q^a Y_{ab} q^b H$$

Yukawa matrix

$$Y_{ab} = \begin{pmatrix} 0 & -v/M_F \\ v/M_F & V/M_F \end{pmatrix}$$

$v/M_F = \sqrt{x}$

$V/M_F = 1+x$

Is the Gatto's texture