Lattice QCD and New Physics

Federico Mescia
ECM & ICC,
Universitat de Barcelona

- *Outline*

❶ Flavour Physics and New Physics:

➲ High Precision calculations: Lattice QCD

❷ Opportunity of new physics and Lattice QCD

➲ Charged Current modes: $K\to\mu\nu$, $B\to\tau\nu$, $B\to D\tau\nu$: ***H^+, right-handed current ...***

➲ Flavour Changing Neutral Current observables: ΔM_s, ε_K, $B\to K^*\mu\mu$: ***H^0, gluino ...***

Super B, Benasque, January 18-21, 2011

Flavour Physics and New Physics

Next Hints for the Quark Flavour sector mostly driven by the modes

1. CP asymmetry in $B_s \to \psi\phi$. $\beta_s^{SM} \approx 0$
2. $B_s \to \mu\mu$
3. $K \to \pi\nu\nu$
4. $K_{\mu 2}/K_{e2}$

LHCb (1, 2) — **NA62-JPARC** (3, 4)

➲ For these modes, hadronic uncertainties are not a big issue!!:

➲ However, *to discriminate among NP models we will need much larger set of flavour-changing processes =>*

$B \to \tau\nu$, $B \to D\tau\nu$, $B \to \pi(\rho) l\nu$, ΔM_s, ε_K, $B \to K^*\mu\mu$ — **Super B**

➲ **KEY POINT**: to *keep under very good control hadronic uncertainties*

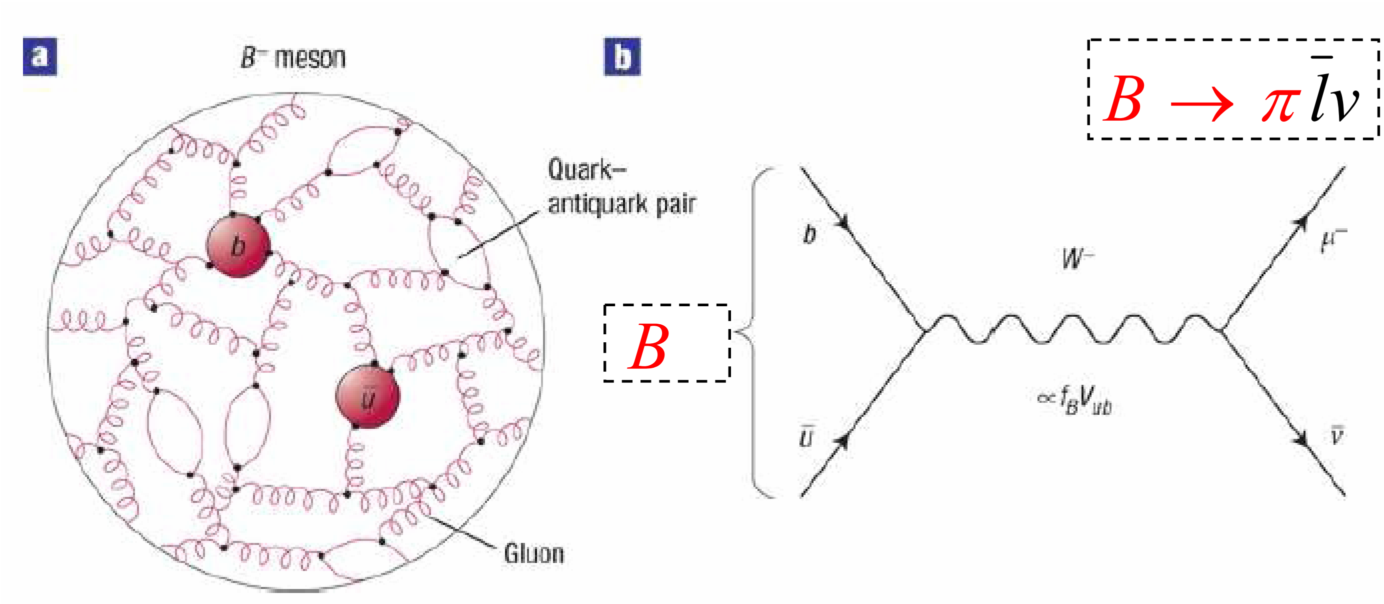
→ ***LATTICE QCD?***

Flavour Physics: New Physics vs QCD effects

☺ *Changes of quark flavour inside a hadron are weak interaction processes:*

$\rightarrow L_{eff}(M_W) \rightarrow$ OPE

B



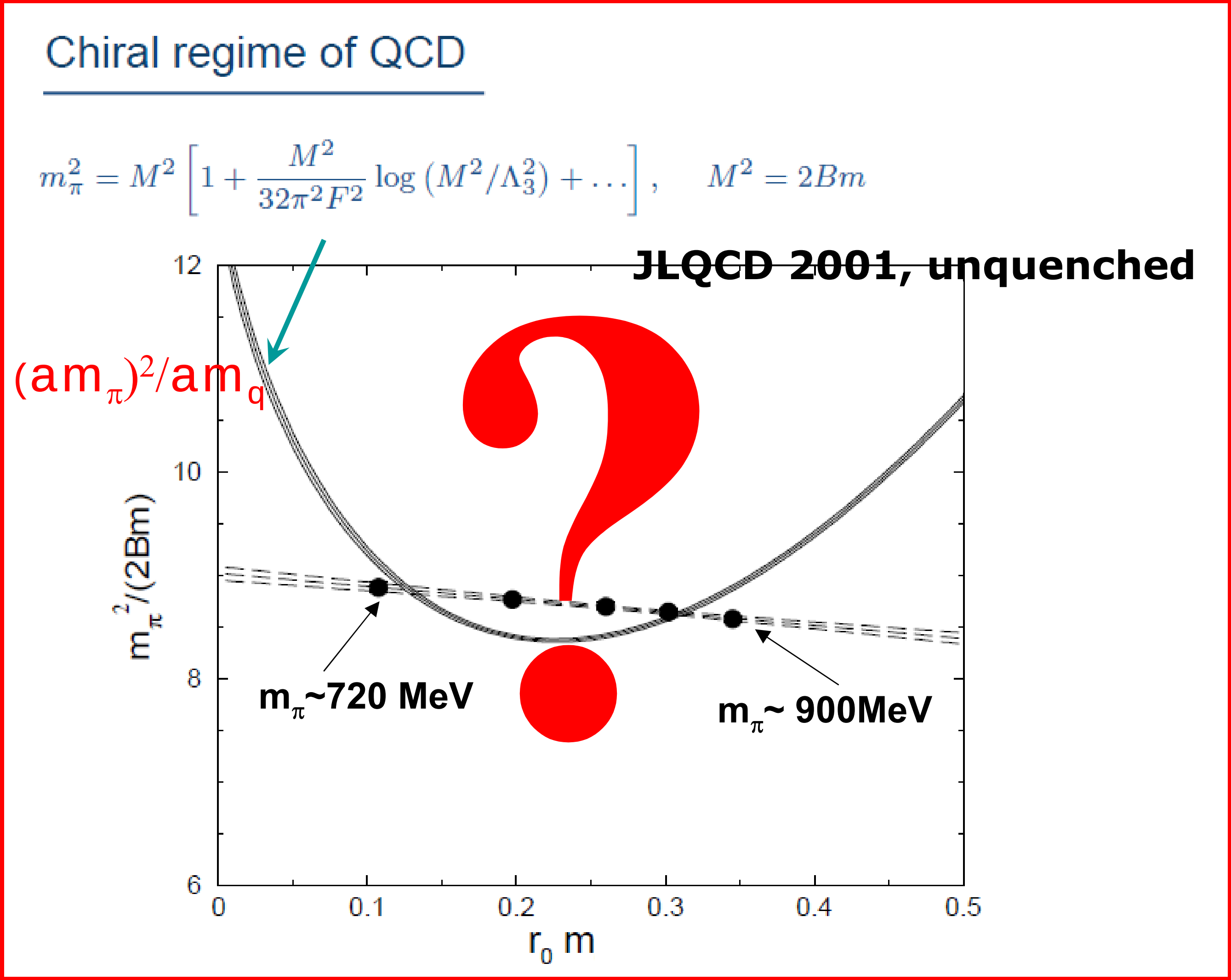
⇨ *Due to confinement, QCD effects are significant and non-perturbative* ☹

⇨ *QCD effects absorbed into hadronic matrix elements*

A task for Lattice QCD -> tremendous progress in the last years!

Chiral Regime of QCD

A problem with (old) lattice simulations:
Heavy pion mass!



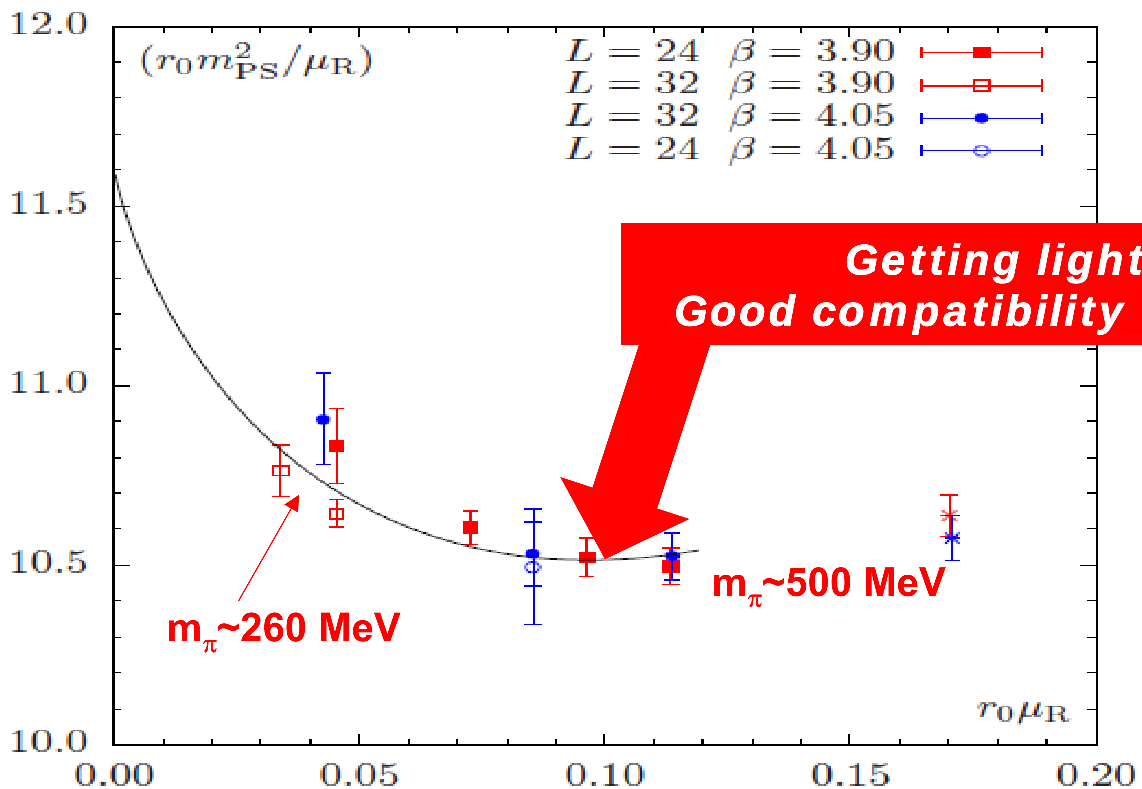
Incompatibility with ChPT?

Chiral Regime of QCD

No longer problems with (new) lattice simulations
Good compatibility with ChPT

$$m_\pi^2 = M^2 \left[1 + \frac{M^2}{32\pi^2 F^2} \log\left(M^2/\Lambda_3^2\right) + \ldots \right], \qquad M^2 = 2Bm$$

$(am_\pi)^2/am_q$



am_q

ETMC arXiV:0803.0224

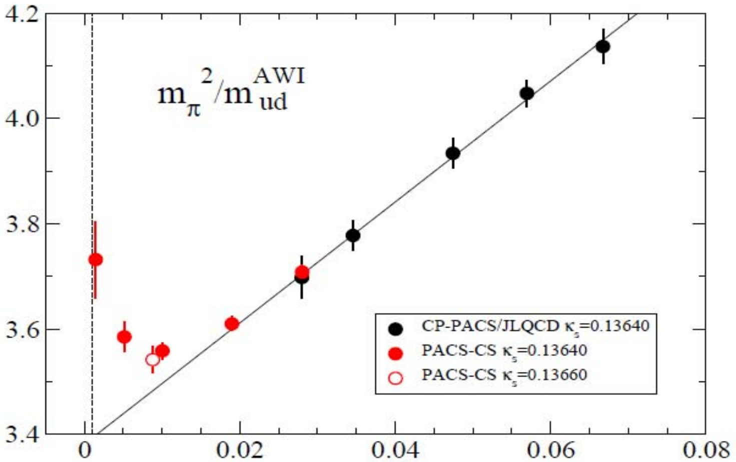
2006-08, unquenched, Wilson-like fermions ☺

Similar plots by other collaborations (using different approaches)

Chiral regime of QCD

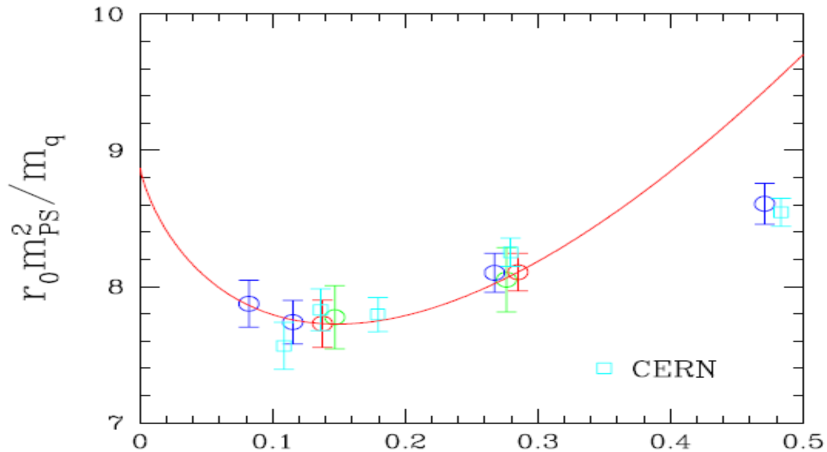
$(am_\pi)^2/am_q$

Hints of chiral Logs



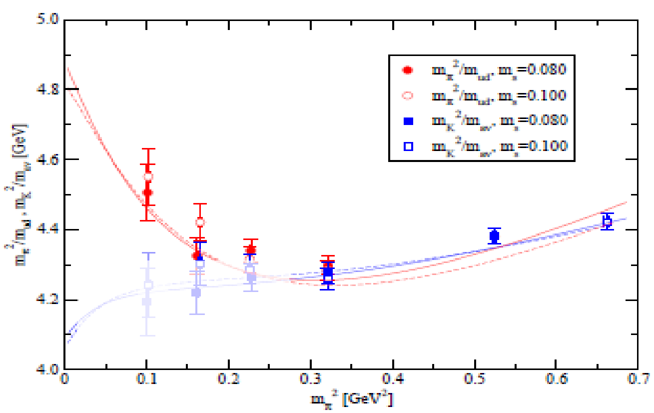
PACS-CS'08, N_F=2+1, Clover:

a=0.09 fm, M_π=156 MeV, $L M_\pi$ ~2.3!!



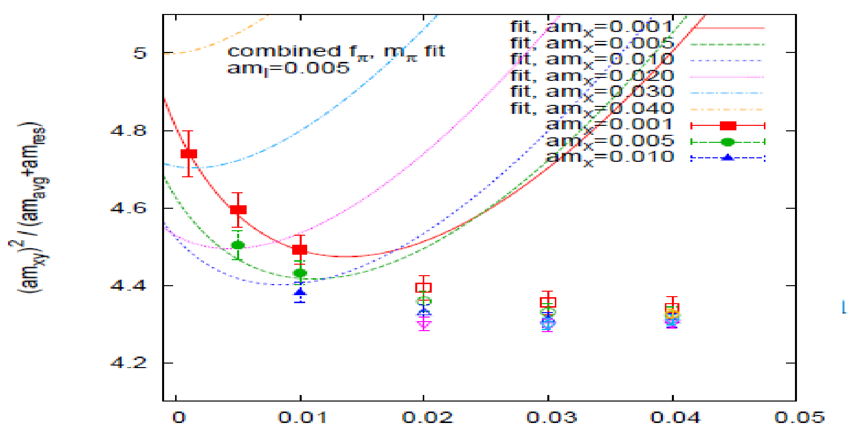
QCDSF'08, N_F=2, Clover:

a=0.07 fm, M_π=313 MeV, LM_π ~4



JLQCD/TWQCD'08, N_F=2+1, Overlap:

a=0.11 fm, M_π=300 MeV, $L M_\pi$ ~2.6!!



RBC/UKQCD'06, N_F=2+1, DWF

a=0.114 fm, M_π=310, LM_π ~3-4

What about phenomenology?

★ *Up to now, only a few observables available from first principle QCD action* **(2006 - on)**

➲ ***Wilson-like & Domain-Wall fermions***

■ some observables are still in the "quenched approximation" (1974-2002);

● most unquenched estimates are from staggered fermions **(MILC: 2002 – on)**

☺ ***First realistic QCD study => MILC opened up unquenched era!!***

😐 *but problematic for a SuperB era!:*

➲ *staggered ansatz:* $\det[D_{NF=1}] \cong \det[D_{stag}]^{1/4}$ to eliminate spurious "tastes":

➲ *non-local theory!* Shamir, Bernard, Golterman, Sharpe, Creutz '04-'08

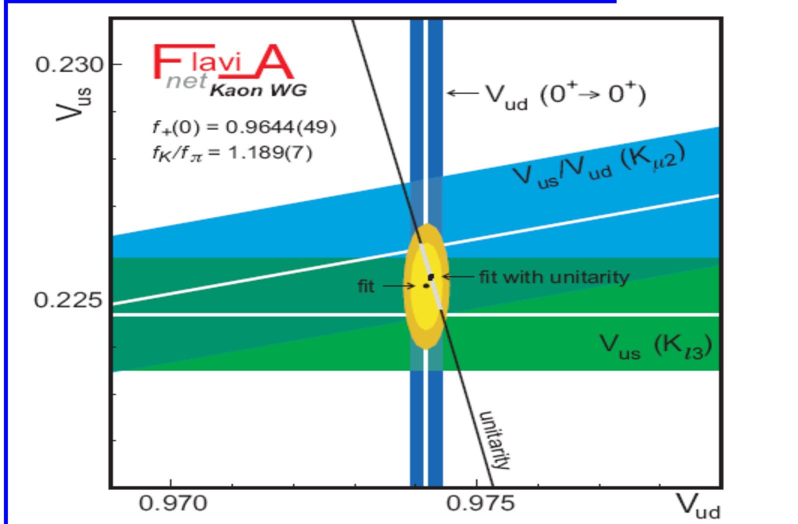
➲ ***QCD when lattice spacing goes 0?***

➲ ***at finite a, significant lattice artefacts: to subtract by complicated fit***

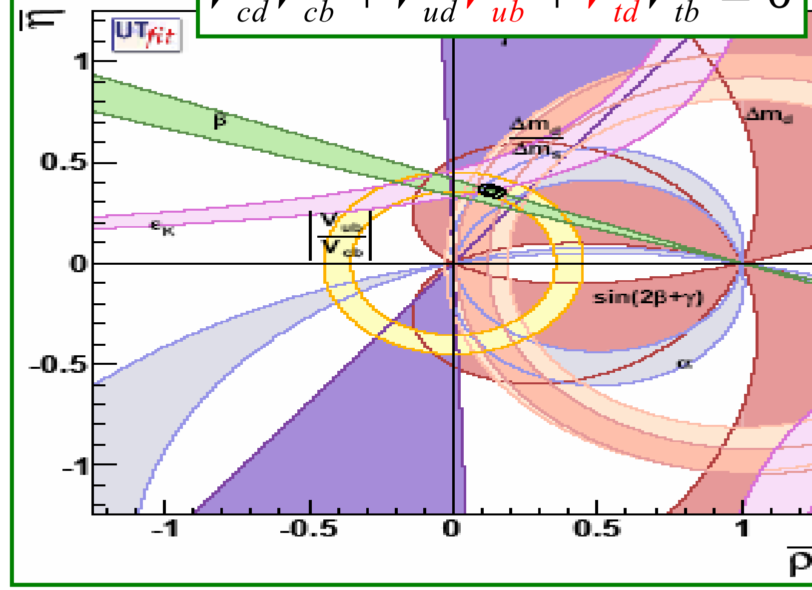
😐 *Lattice study from first principle action still need some time but progress already visible*

Lattice QCD and Flavour Physics

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



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



K→lν: exp. err *0.2%* ★★

lattice err. on f_K/f_π :

2-3% (2006)→**0.5%** (2010)

K→πlν: exp. err *0.2%* ★

lattice err. on $f_+(0)$:

0.9% (2006)→**0.5%** (2010)

B→D(D*)lν: exp. err *1.5%* ● ■

lattice err. on *F(1) & G(1)* :

5% (2006)→**2.5%** (2010)

ε_K: K^0-$\bar{K}^0$ mixing
exp. err *0.5%*

lattice err. on B_K: ★

11% (2006)→**4%** (2010)

ΔM_d: B^0_d-B^0_d mixing
exp. err *1%*

lattice err. on $f_{Bd}\sqrt{B_{Bd}}$: ●

13% (2006)→**6%** (2010)

ΔM_s: B^0_s-B^0_s mixing
exp. err *0.7%*

lattice err. on $f_{Bs}\sqrt{B_{Bs}}$: ●

13% (2006)→**6%** (2010)

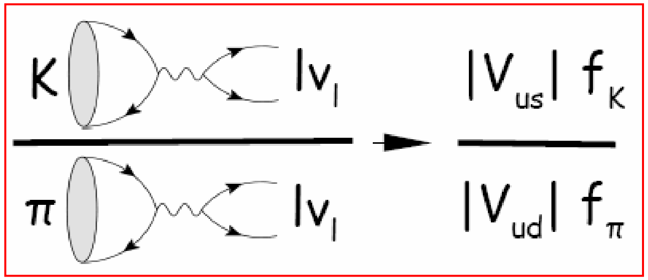
B→π(ρ)lν:
exp. err *10%*

lattice err. on $f_+(q^2)$: ● ■

11% (2007)!

★ Simulation from first-principle action. ■ Quenched simulation. ● Staggered fermions

f_K/f_π: an example of Modern lattice measure



Hadronic uncertainties from

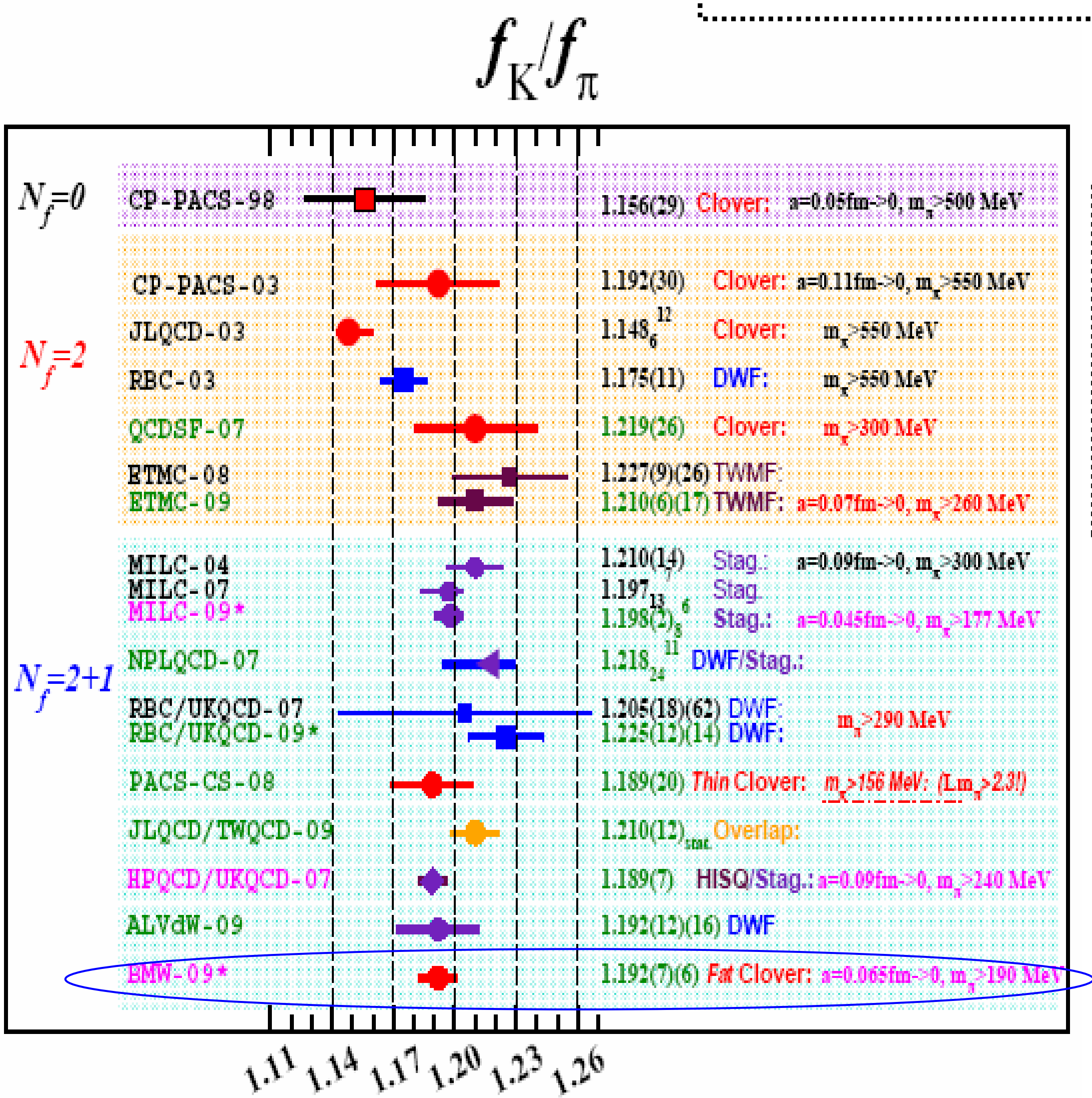
$$\langle 0 | \bar{s}\gamma^\mu\gamma_5 u | K \rangle = p^\mu f_K$$

$$\langle 0 | \bar{d}\gamma^\mu\gamma_5 u | \pi \rangle = p^\mu f_\pi$$

f_K/f_π: lattice enters high precision era

❖ ***No Competition from non-Lattice approaches:***

$$f_K/f_\pi = 1 + (m_K^2 - m_\pi^2) \times \text{unknown-coef.}$$



Lattice systematic under control!

- ❑ **Independent determinations** (Wilson-like, Domain Wall, Stag.);
- ❑ **Many lattice spacings** (Continuum Limit reached);
- ❑ **Light m_π~190 MeV**;
- ❑ **Finite size effects under control.**

$$f_K/f_\pi = 1.193 \pm 0.006 \ \ [0.5\%];$$

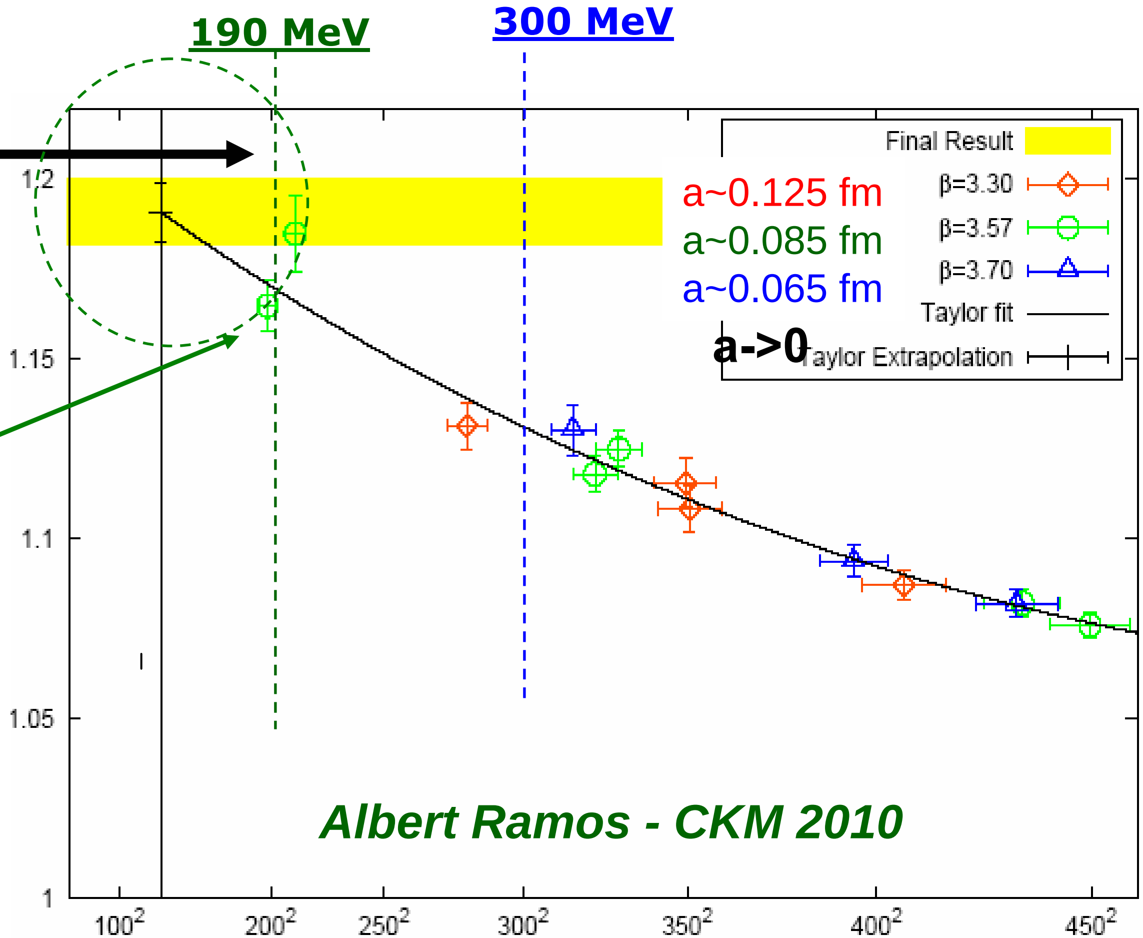
$$f_K/f_\pi - 1 = 0.193 \pm 0.006 \ \ [3\%]$$

good prospects to improve f_K/f_π-1 to 1% accuracy?

f_K/f_π - Evaluations

• *getting very close to the physical point;* **190 MeV**

The final result extrapolated at the physical pion is only 2% above the lightest point simulated! ☺



- **BMW result: N_F=2+1, *Clover*, a=0.06->0, $m_\pi \geq 190$ MeV, L $m_\pi \sim 4$**

f_K/f_π=1.192(7) (6) => σ_{rel} ~0.75% **($\delta_{SU(3)}$~5%)**

Durr, Fodor, Hoebling, Katz, Krieg, Kurth, Lellouch, Lippert, Ramos, Szabo, hep-lat 1001.4692

Constrain on scalar densities: $SM + \left(\bar{s}_R u_L\right)\left(\bar{\ell}\nu_L\right)$

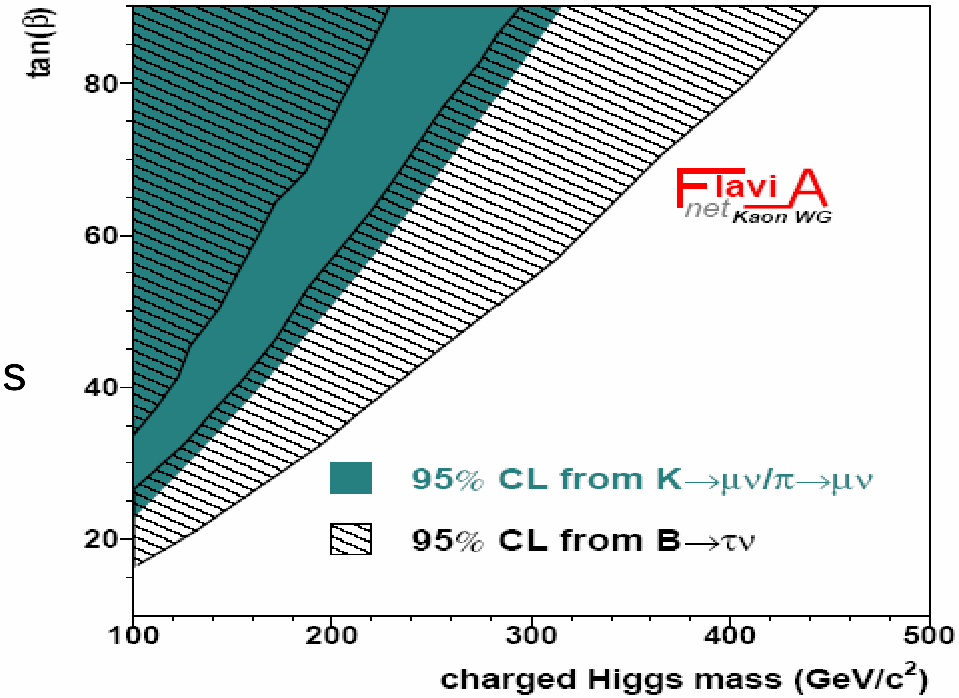
$$\frac{B(K\to\mu\nu)}{B(\pi\to\mu\nu)}\times\frac{B(n\to pl\nu)}{B(K\to\pi l\nu)}=\left(\frac{f_K}{f_\pi}\frac{1}{f_+(0)}\right)^2\times\left(1+g^H\frac{m_K^2}{m_{H^+}^2}\right)^2$$

$$Br(B\to\tau\nu)\propto\left|V_{ub}\right|^2 f_B^2 m_B m_\tau^2\times\left(1+g^H\frac{m_B^2}{m_{H^+}^2}\right)^2$$

Example MFV@large tanβ $g^H=-\tan\beta^2/(1+\varepsilon_0\tan\beta)$

Kaon: *NP highly suppressed* => but favourable *exp.* and *th.* scenario

B-physics: *large NP effects* => but *exp.* and *th.* accuracy under progress

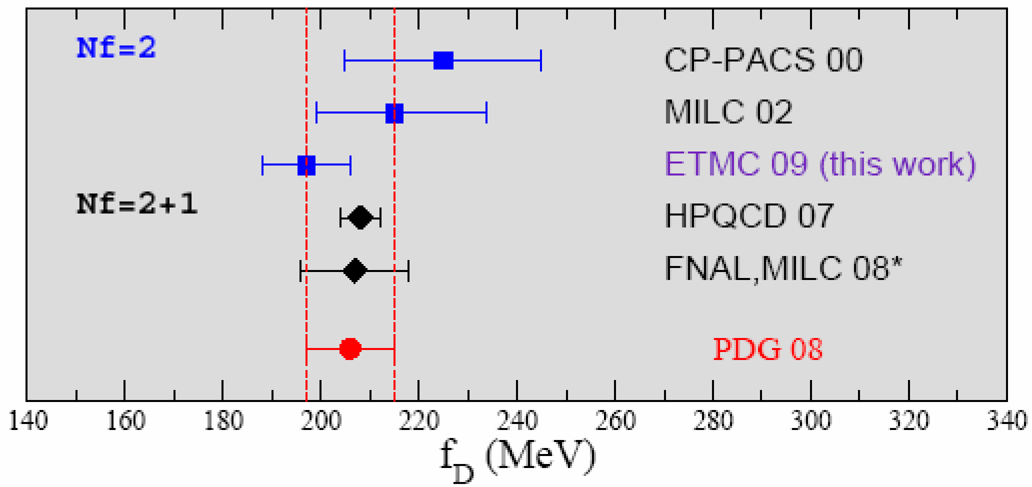


Present picture very reassuring and compatible between B and K physics.

2008 f_{Ds} puzzle: 3-4σ deviation with experiments?

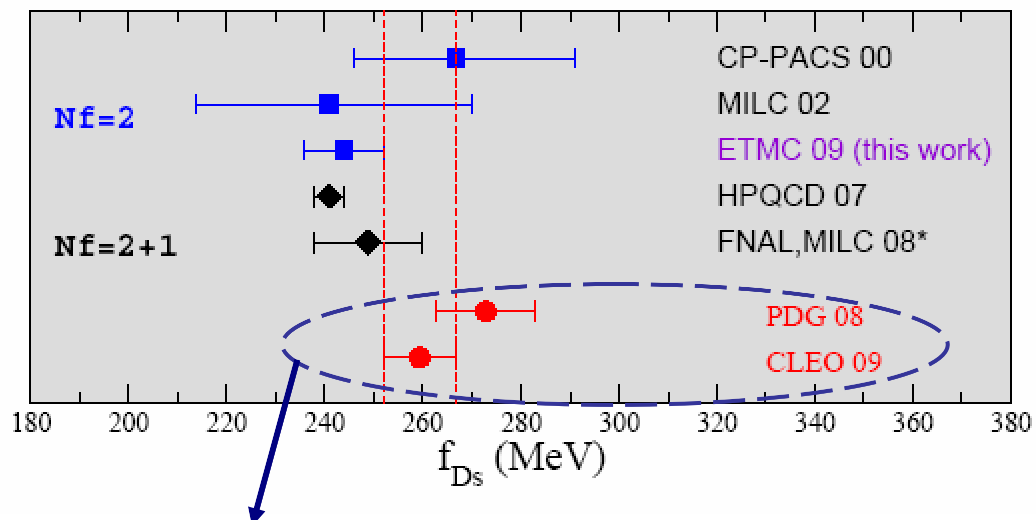
2008 f_{Ds} puzzle: 3-4σ deviation with experiments?

- ***f_D and f_{Ds} recently measured at CLEO, BaBar and Belle with good accuracy!*** *(assuming CKM unitarity)*



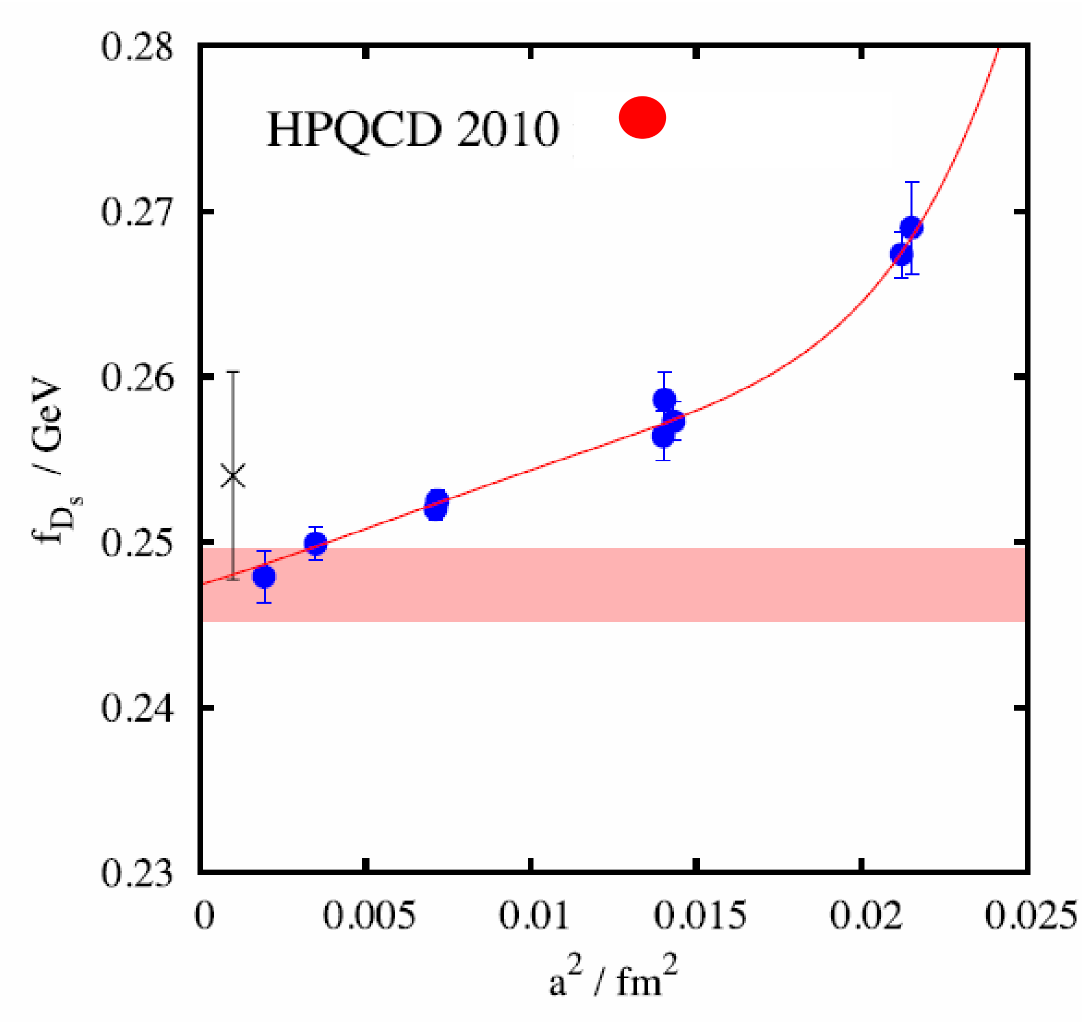
- ***Key cross check of Lattice QCD before reach B-physics.***

- ***Overall consistency of lattice results;***



f_{Ds} "puzzle" weakened by CLEO-c 2009 accurate measurement

Eduardo Follana (U. Zaragoza)



Staggered fermions

"Puzzle" seems to disappear:

No conclusive evidence for New Physics in the charm quark sector yet, but the $D_{(s)}$ leptonic decays will continue to help constraining SM extensions

$\Delta F=2$ observables:
ε_K (B_K), ΔM_d and ΔM_s (fB and Bb)

- ❑ Important role for the SM Unitarity Triangle analysis [UTfit and CKMfitter] :
- ❖ **strong constraints for non-minimal flavour models:**
  - ➲ **MSSM** -> generic down squark insertion [Gabbiani et al. 1994, …]
  - ➲ **Little Higgs** [A. Buras et al. 2004]

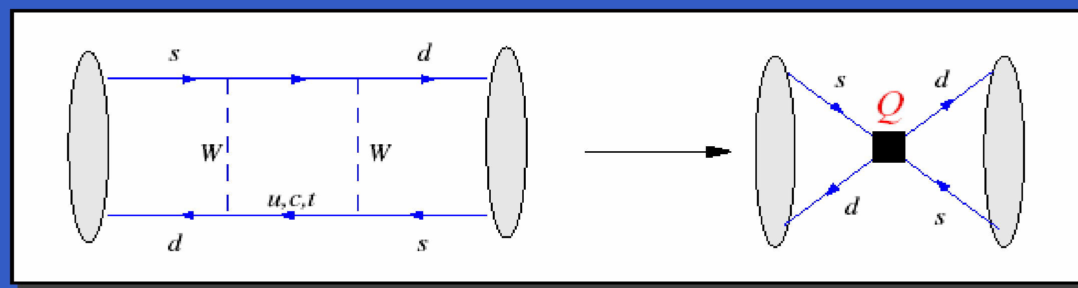
Lattice role and New Physics Opportunities!

CP-Violation in K – $\bar{K}$ Mixing: ε_K and B_K

$$K_L \sim \underbrace{(K^0 - \bar{K}^0)}_{CP=-1} + \varepsilon_K \underbrace{(K^0 + \bar{K}^0)}_{CP=+1}$$

$\varepsilon_K \rightarrow$ indirect CP-violation

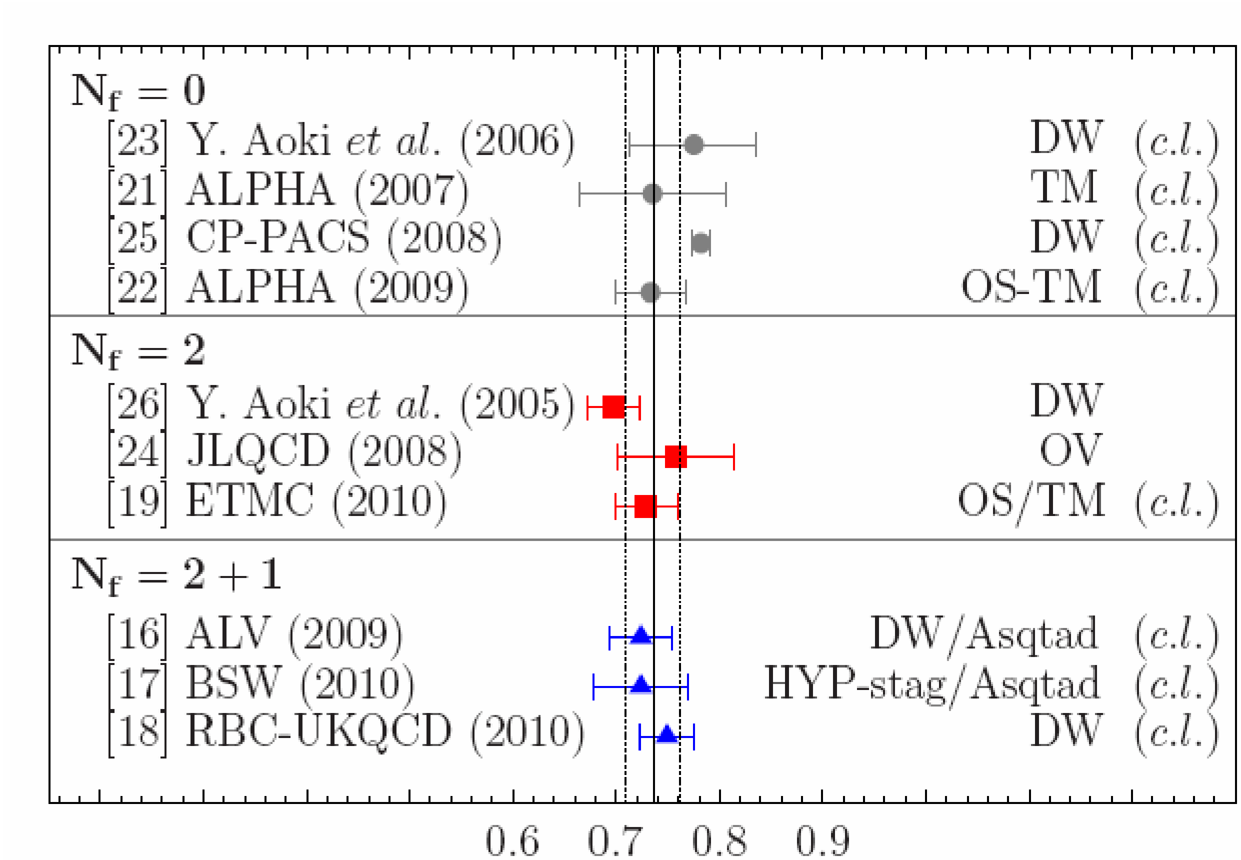
The Effective ΔS=2 Hamiltonian



$$\varepsilon_K \sim \langle \bar{K}^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | K^0 \rangle = C(\mu) \cdot \langle \bar{K}^0 | \overbrace{\bar{s}\gamma_\mu(1-\gamma_5)d \; \bar{s}\gamma_\mu(1-\gamma_5)d}^{Q(\mu)} | K^0 \rangle$$

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

Dramatic progress in B_K evaluation from recent simulations



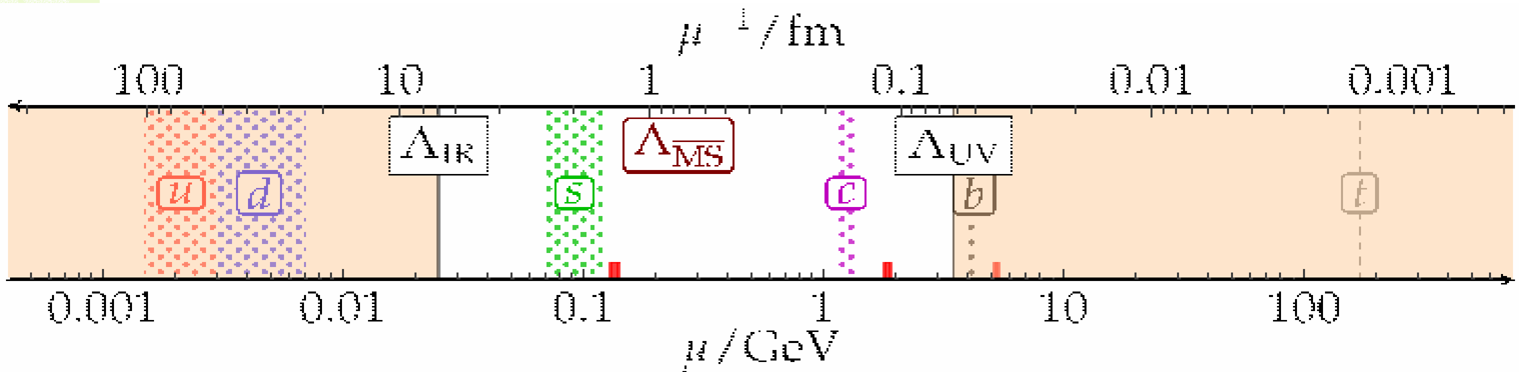
Average by FLAG WG (1011.4408 [hep-lat])*:* $\mathbf{B_K = 0.724(30)}$ (4%)

- *current value lower than old $N_F=0$: $B_K \sim 0.83(6)$*

key observation (2000): to exploit χ–improved action -> among others Carlos Pena (UAM), Pilar Hernandez (IFIC)

- increase the tension in the UTA

Challenge of B-physics: the multi scale-problem of QCD



hierarchy of disparate physical scales to be covered:

$$\Lambda_{IR} = L^{-1} \ll m_\pi, \ldots, m_D, m_B \ll a^{-1} = \Lambda_{UV}$$

$$\left\{ O(e^{-L m_\pi}) \Rightarrow \boxed{L \gtrsim \frac{4}{m_\pi} \sim 6\,\mathrm{fm}} \right\} \curvearrowright \; L/a \gtrsim 120 \; \curvearrowleft \left\{ a m_D \lesssim \frac{1}{2} \Rightarrow \boxed{a \approx 0.05\,\mathrm{fm}} \right\}$$

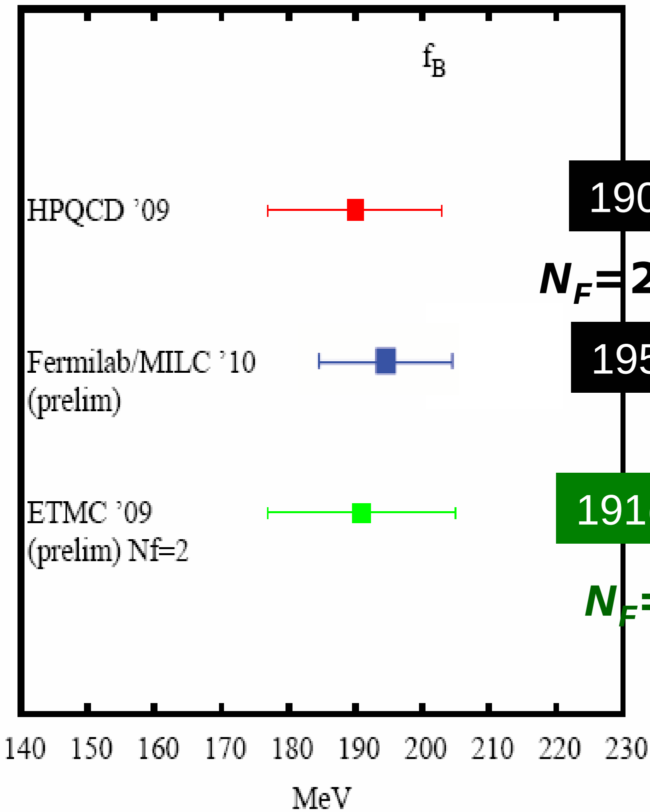
Currently, *b* quarks cannot be directly simulate at their physical mass due to large discretization errors (a m_b« 1)

- *effective theory: like NRQCD action*
- *simulate heavy quark in the charm region and extrapolate to the B:*

f_B - f_{Bs} : *unquenched results*

☺ Overall picture satisfactory
☺ Continuum Limit

☹ A few independent determinations (Wilson-like, Stag.);
☹ Still coarse lattice spacing at N_F=2+1



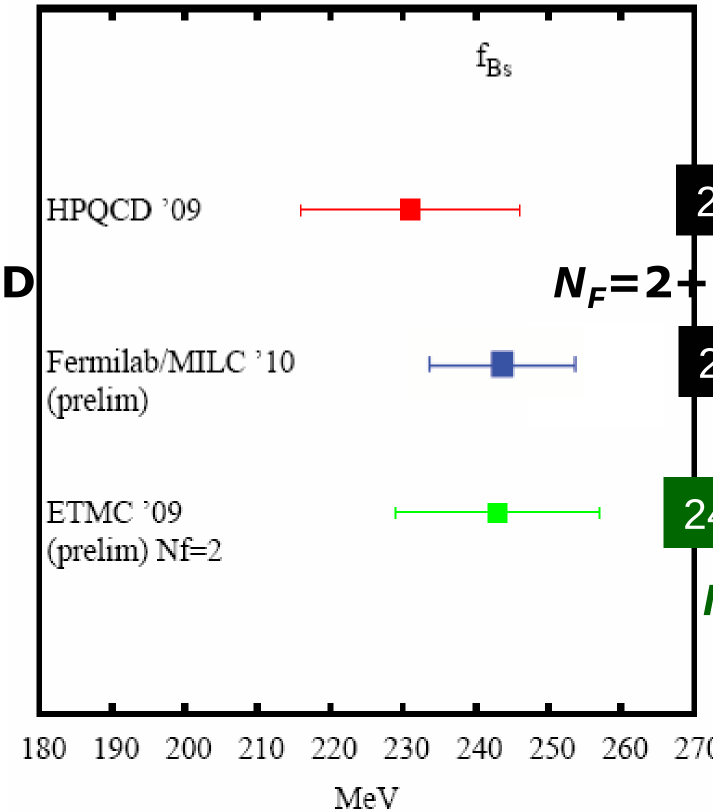
190(13) (7%)

N_F=2+1 - NRQCD

195(11) (6%)

191(14) (7%)

N_F=2, rel. b



231(15) (6%)

N_F=2+1 - NRQCD

243(11) (4%)

243(14) (6%)

N_F=2, rel. b

Average (Laiho, Lunghi, Van de Water '10)

f_B = 192.8(9.9) MeV (5%) f_{Bs} = 238.8(9.5) MeV (4%)

Comments:

- ***Effective theory approach: discretized NRQCD action***

  - *Quite Sophisticated procedure!*

    - *larger set of $1/m_Q$ corrections on the lattice w.r.t the continuum*
    - Improved through $O[1/m_Q^2, a^2]$ and leading terms $O[1/m_Q^3]$
    - $O[\alpha_s^n/(am_Q)]$ divergences to be subtracted to get the continuum limit

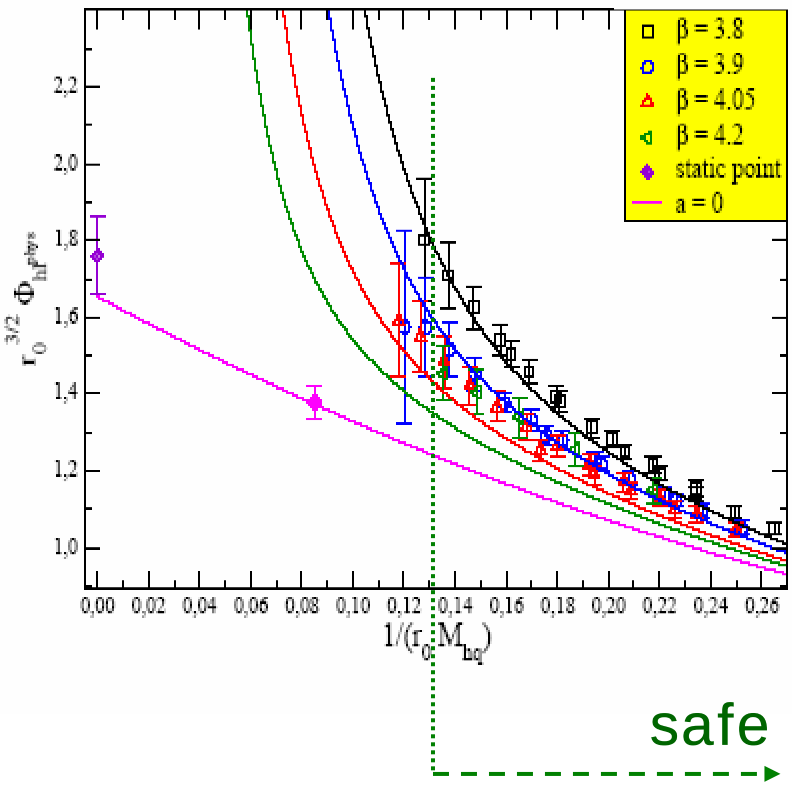
  - *On the other hand, large experience by HPQCD*
    (Eduardo Follana, Elvira Gamiz (Granada)).

- ***Pratical approach (a la San Tommaso) welcome***

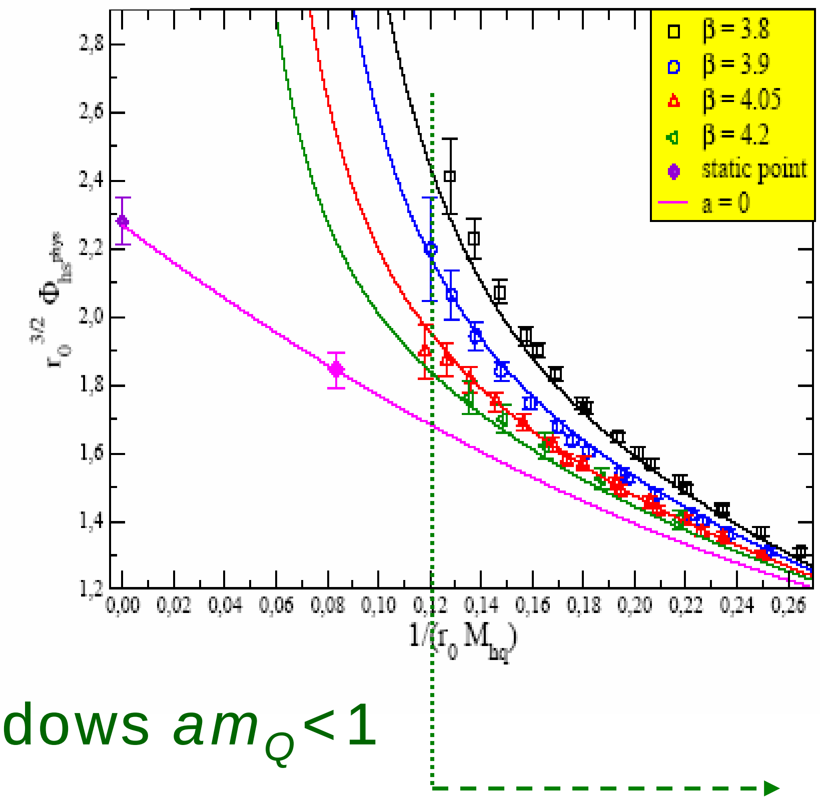
- Pratical approach (a la San Tommaso): ETMC

$$\Phi = f_B\sqrt{M_B}$$

f_B



f_{Bs}



safe windows $am_Q<1$

- *HQET-guided extrapolation*
- *Combined fit with the static point, $m_b=\infty$*
- *Larger safe windows with smaller a~6 GeV*

ΔM_d and ΔM_s

$$\Delta Ms :< B | \bar{b}_L \gamma^\mu s_L \bar{b}_L \gamma^\mu s_L | \bar{B} > \propto \hat{B}_{Bs} f_{Bs}^2.$$

$$\Delta Md :< B | \bar{b}_L \gamma^\mu d_L \bar{b}_L \gamma^\mu d_L | \bar{B} > \propto \hat{B}_{Bd} f_{Bd}^2$$

☹ ***Only one NF=2+1 calculation available from HPQCD – Staggered fermions***

(Eduardo Follana, Elvira Gamiz)

☹ ***Continuum Limit – still coarse lattice spacing*** ☹

$$\hat{B}_{Bd} = 1.26(11) -> (9\%) \qquad \hat{B}_{Bs} = 1.33(6) -> (5\%)$$

❖ ***reassuring scenario but we need further calculation from several groups!***

Average (Laiho, Lunghi, Van de Water '10)

$f_{Bs}\sqrt{B_{Bs}}$ = 275(13) -> 5%!!? ξ = 1.243(28) -> 2%

$$\xi \equiv \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$

$\Delta F=1$ $b\to u$, $b\to s$ transitions:

$B\to \pi\,(\rho)\,l\nu$,

$B\to K^{*}\mu^{+}\mu^{-}$,

$B\to K^{*}(\phi)\gamma$

☹ very preliminary unquenched activities

-> pratically as bad as quenched era

☹ further complication -> form factors = $f(M_B,\ M_\pi,\ q^2)$

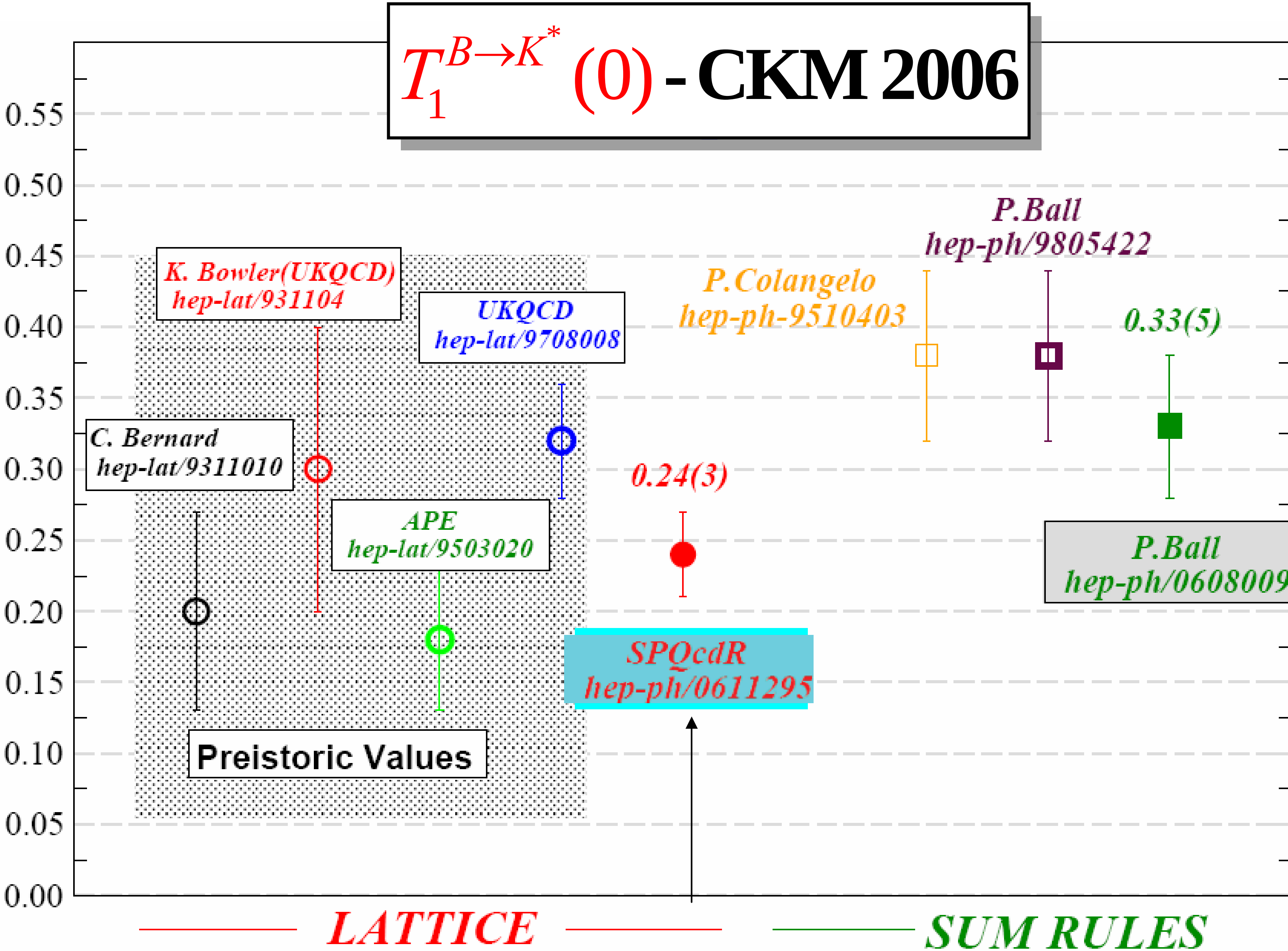
$$A(B \to K^* \mu\mu) = \langle K^* | Heff | B \rangle = \begin{cases} C_7 \times \bar{b}\sigma^{\mu\nu} s F_{\mu\nu} \\ C_9 \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu} l + C_{10} \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu}\gamma_5 l \\ C_S \times \bar{b}_L s_R \bar{l}l \end{cases}$$

➢Matrix elements ⇔ 7 form factors **Lattice QCD**

$$\langle K^*(p_{K^*})|\bar{s}\gamma_\mu P_{L,R} b|B(p)\rangle = i\epsilon_{\mu\nu\alpha\beta}\epsilon^{\nu *} p^\alpha q^\beta \frac{V(q^2)}{m_B + m_{K^*}} \mp$$
$$\mp \frac{1}{2}\Big\{ \epsilon^*_\mu (m_B + m_{K^*}) A_1(q^2) - (\epsilon^* \cdot q)(2p - q)_\mu \frac{A_2(q^2)}{m_B + m_{K^*}} -$$
$$- \frac{2 m_{K^*}}{q^2} (\epsilon^* \cdot q)[A_3(q^2) - A_0(q^2)] q_\mu \Big\},$$

$$\langle K^*(p_{K^*})|\bar{s} i\sigma_{\mu\nu} q^\nu P_{R,L} b|B(p)\rangle = -i\epsilon_{\mu\nu\alpha\beta}\epsilon^{\nu *} p^\alpha q^\beta T_1(q^2) \pm$$
$$\pm \frac{1}{2}\Big\{ [\epsilon^*_\mu (m_B^2 - m_{K^*}^2) - (\epsilon^* \cdot q)(2p - q)_\mu] T_2(q^2) +$$
$$+ (\epsilon^* \cdot q)\left[q_\mu - \frac{q^2}{m_B^2 - m_{K^*}^2}(2p - q)_\mu \right] T_3(q^2) \Big\}.$$

☹ Up to now, only $T_1(0)$ on the Lattice but quenched (Becirevic, Lubicz, F.M. '06)



D. Becirevic, V. Lubucz and F. M., 2006

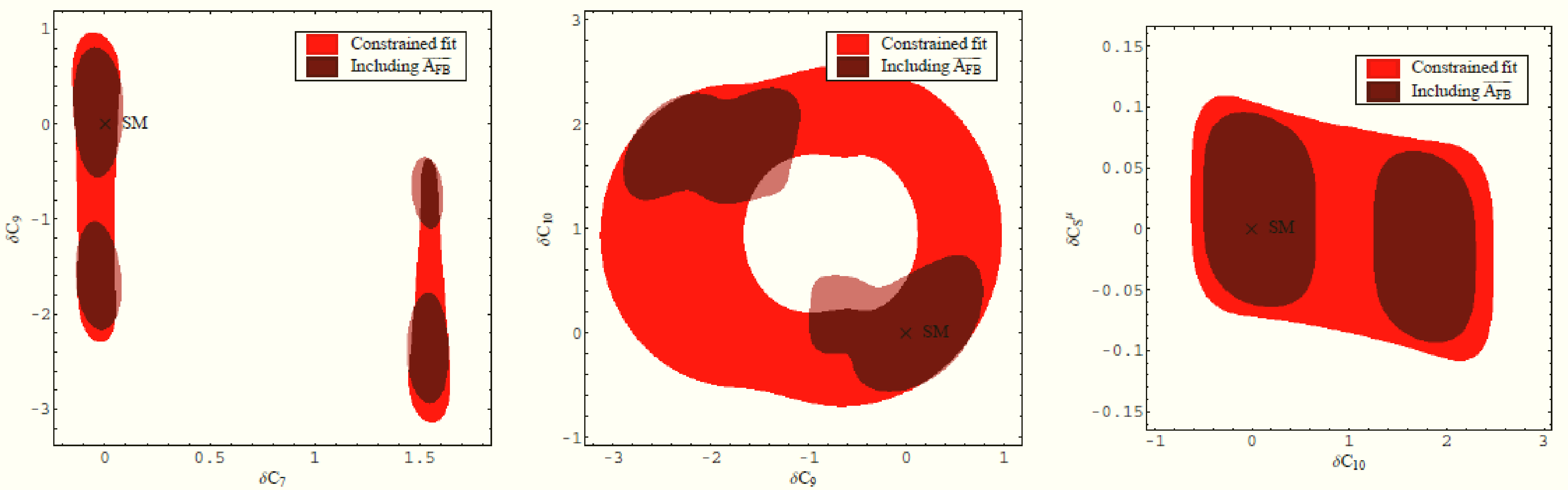
$A_{FB}(B_d \to K^* l^+ l^-)$, already plays a special role:

❖ very large experimental error;

➲ **Necessary to improve lattice form factors!**

$A_{FB}(B_d \to K^* l^+ l^-)$: **2 bins** ***exp*** **(large):** *Babar+Belle '09*

$[q^2 < 6.25\ \mathrm{GeV}^2]$	$0.24^{+0.19}_{-0.24}$	-0.01 ± 0.02
$[q^2 > 10.24\ \mathrm{GeV}^2]$	$0.76^{+0.53}_{-0.34}$	0.20 ± 0.08 [2



***Model-independent Analysis* in MFV!**

FCNC constraints from $Br(B_d \to X_s \gamma)$, $Br(B_d \to X_s l^+ l^-)$, $Br(B_d \to \mu^+ \mu^-)$, ΔM_s

Hurth, Isidori, Kamenik, F.M '08

$D \to \pi \ell \nu_\ell$

Lattice QCD for D, NF=2 unquenched

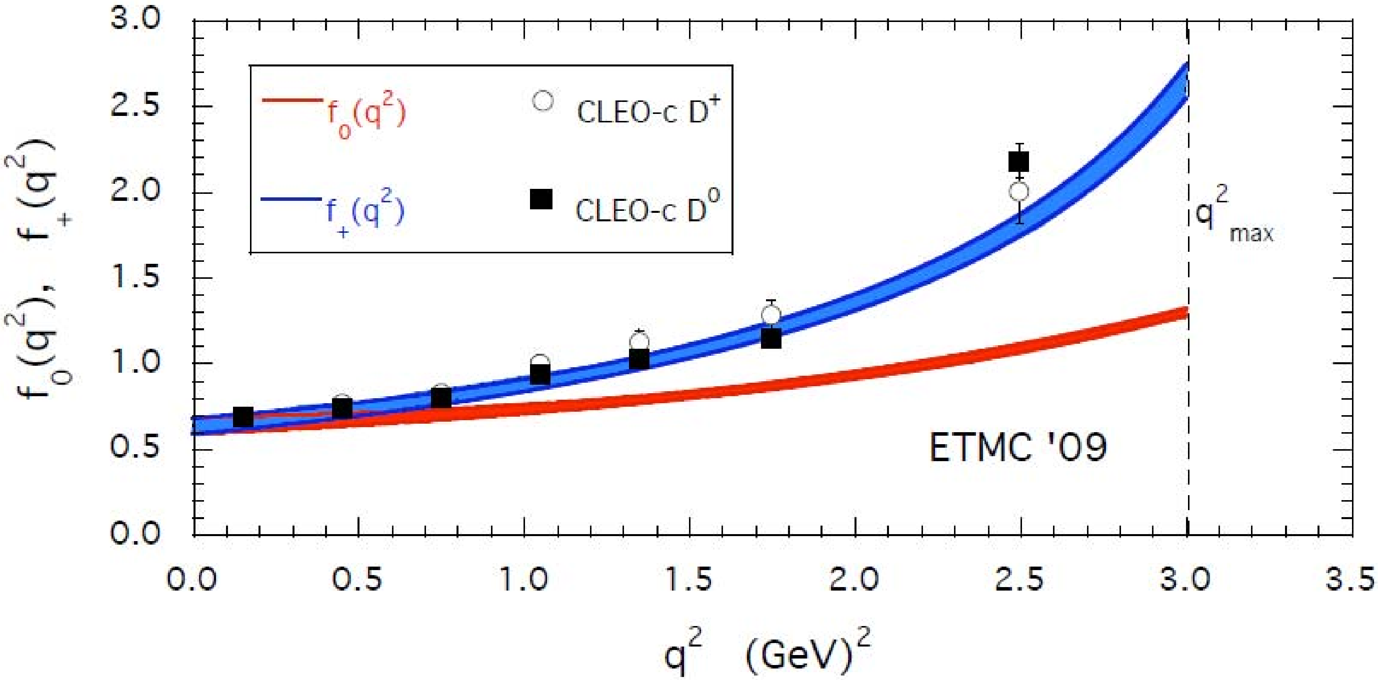


Figure 3: *Vector [$f_+(q^2)$] and scalar [$f_0(q^2)$] form factors for the $D \to \pi \ell \nu_\ell$ decay versus the squared*

ETMC et al., '09

Lattice Flavour Physics in Spain

☺ 3 international collaborations: **ETMC**, **HPQCD**, **CLS**

☹ ***1 Mare Nostrum!***

Conclusions:

LATTICE QCD -> touchable progress in recent years:

- reliable *unquenched simulations with pions close to the physical point =>* m_π=156 MeV (PACS-CS), $\mathbf{m}_\pi$=190 MeV (BMW)
- *f_K/f_π paradigma of present lattice progress!*
- *many other calculations should be come soon!*

In particular, for B-physics observables

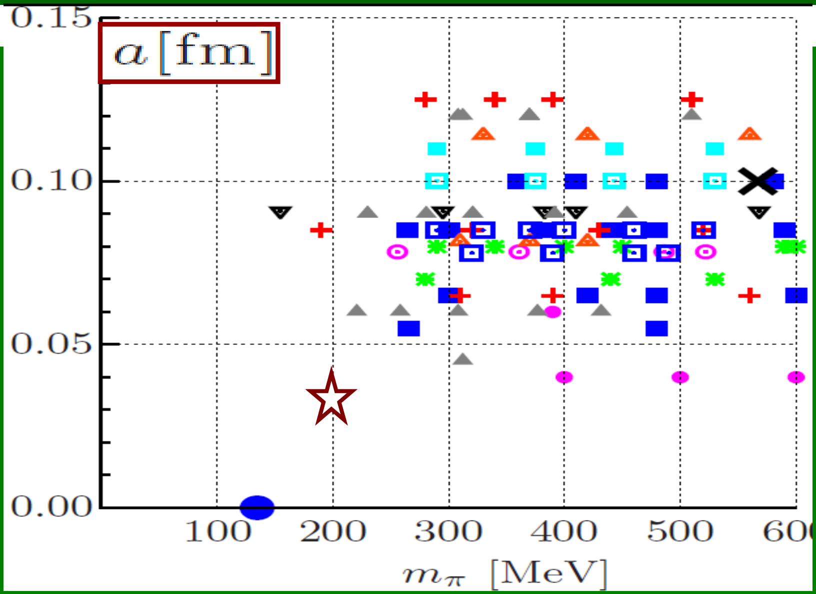
Still a long work to assess 1%-precision needed at Super-B

1. ***discretization errors:*** $a*m_B \ll 1$

   => **$a \sim$ 0.033 *fm*** (6 *GeV*): ($a \geq$ 0.07 *fm*)
2. ***finite volume effects:*** $L*m_\pi \gg 1$

   => $L \geq$ **4.5 *fm*** ($L \leq$ 3 *fm*)
3. ***chiral regime:*** **200 ≤ m_π ≤ 300 MeV**

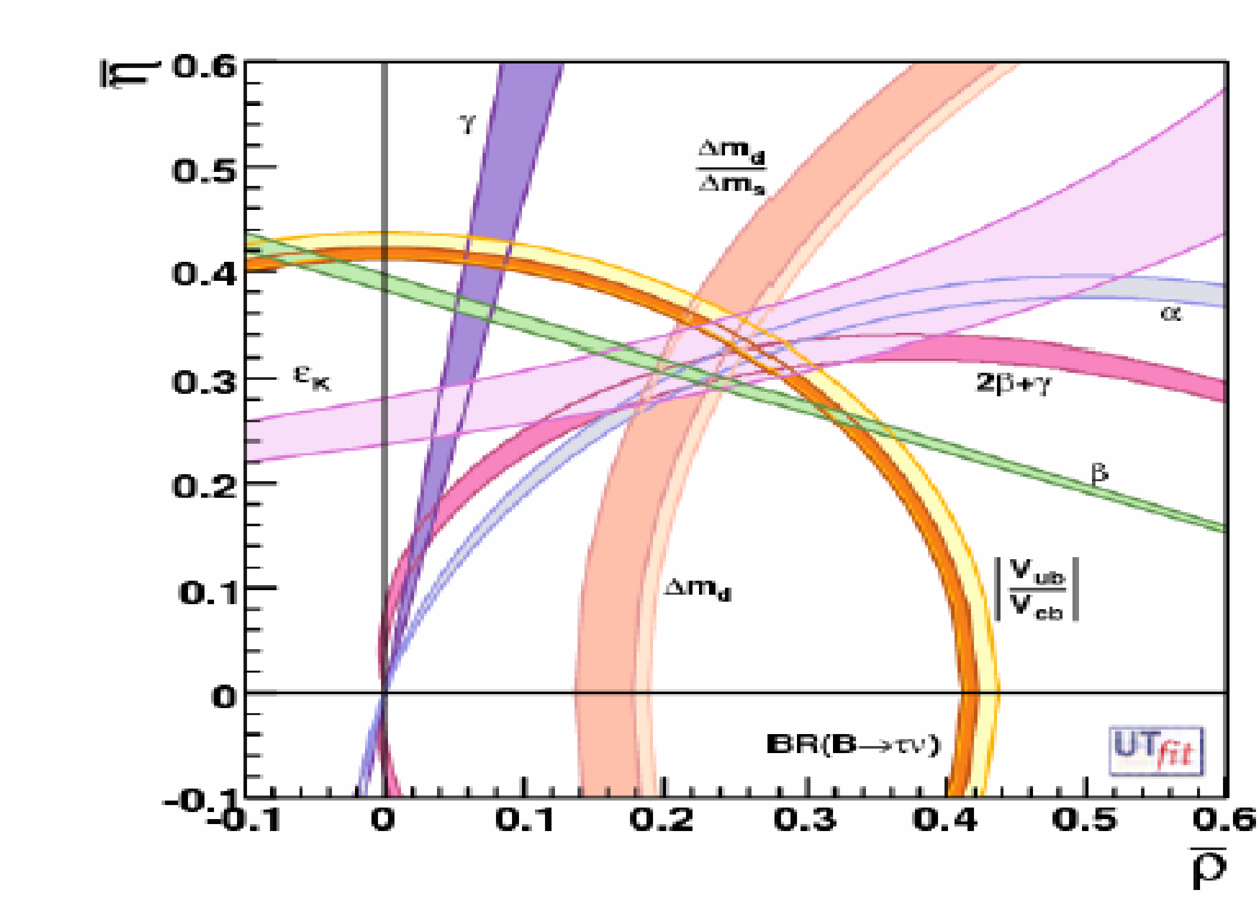
V. Lubicz Super-B report.



courtesy of G. Herdoiza

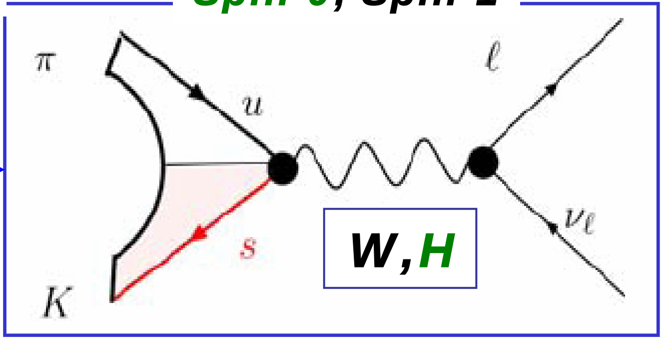
Super B and Lattice QCD Alliance

- ***Constraining V_{us}, V_{ub}, ρ, η as precisely as possible from as many independent modes as possible in order to search for New Physics!***

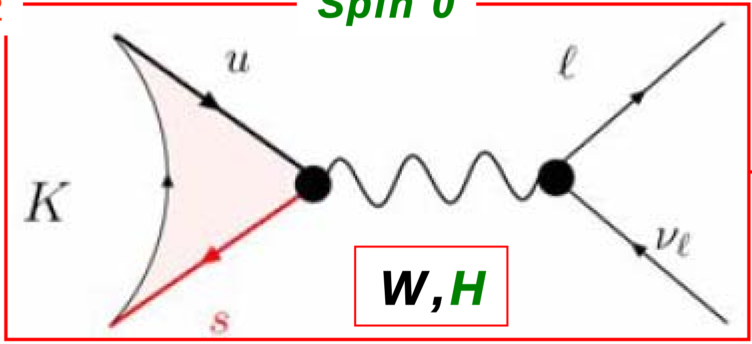


2HDM, Susy ...: Charged Higgs => SM + $(\bar{s}_R u_L)(\bar{\ell}\nu_L)$

$K_{\ell 3}$ — *Spin 0*, *Spin 1*



$K_{\ell 2}$ — *Spin 0*



K_{l3} : Higgs effects => $f_0(q^2) \to f_0(q^2)(1 + g^H q^2/m^2_H)$

- to test g^H **=>** *calculate slope and curvature* of $f_0(q^2)$*!*

$|V_{us}|^{Kl3}$ *is* NP free as soon as we use $f_0(q^2)$ from data

K_{l2} : Higgs effects => $|V_{us}|^{Kl2} \to |V_{us}|^{Kl2}(1 + g^H m^2_K/m^2_H)$

- to test g^H **=>** f_K *from theory:* f_K/f_π *better determined*

constrain on scalar densities

[Hadronic uncertainties 0.5%]

$$\frac{B(K\to\mu\nu)}{B(\pi\to\mu\nu)}\times\frac{B(n\to pl\nu)}{B(K\to\pi l\nu)}=\left(\frac{f_K}{f_\pi}\,\frac{1}{f_+(0)}\right)^2\times\left(1+g^H\frac{m_K^2}{m_{H^+}^2}\right)^2(\text{known f.s})$$

similarly search on H^+ from

$B^\pm\to\tau^\pm\nu$

$$Br(B\to\tau\nu)\propto|V_{ub}|^2 f_B^2 m_B m_\tau^2\times\left(1+g^H\frac{m_B^2}{m_{H^+}^2}\right)^2$$

- *hadronic uncertainty -> f_B: ~5% accuracy from Lattice (Lunghi et al. 2009)*

Best for indirect H^+ searches but only feasible at •SuperB

$B^\pm\to D\,\tau^\pm\nu$

$$\frac{d\Gamma(B\to D\tau\nu)}{dq^2}\propto|V_{cb}|^2\rho_V(q^2)\times\left(1-\frac{m_\tau^2}{m_B^2}\left|1+g^H\frac{q^2}{m_{H^+}^2}\right|^2\rho_S(q^2)\right)$$

2. *hadronic uncertainty -> ρ_V,*
-> ρ_S

Only scalar component sensitivity to H^+: opportunity for Lhcb?

but different theoretical and experimental prospects

Quenched simulation. Staggered fermions