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Dynamical Quark Effects in QCD on the Lattice

K. Kanaya
Univ. of Tsukuba
kanaya@rccp.tsukuba.ac.jp

CP-PACS Collaboration:
A. AliKhan, S. Aoki, Y. Aoki, G. Boyd, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, T. Izubuchi, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, J. Noaki, M. Okamoto, M. Okawa, H.P. Shanahan, Y. Taniguchi, A. Ukawa, T. Yoshié

0. Introduction – from quenched to full QCD

1. Light hadron spectrum

2. Quark masses

3. U(1) problem

4. B-Physics

5. Conclusions

CP-PACS

Computational Physics on Parallel Array Computer System
Center for Computational Physics, University of Tsukuba

Peak performance: 614.4 GFLOPS

Main storage: 128GB main storage

MIMD

2048 node processors

3-D hyper-crossbar network

1.1 TB distributed disks

In operation for LQCD simulations since 1996.

Particle physics simulations on the CP-PACS

'96 '97 '98 '99 '00

← quenched QCD ⟶

← full QCD ($N_f = 2$) ——

← heavy quark (b,c, ..) —

← $T > 0$ QCD ——

← DWQCD —

Limitation of the quenched approximation.

⇓

Full QCD simulations

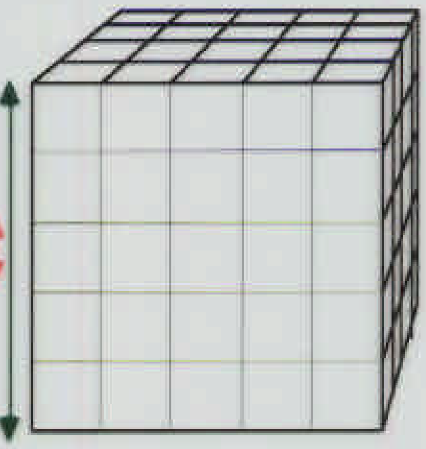
CP-PACS:

first systematic study in full QCD

performing all the extrapolations to remove the lattice artifacts.

0. Introduction – from quenched to full QCD

QCD on the lattice



Simulations on a lattice with

finite lattice spacing a

finite lattice size L

For a physical prediction, we have to

- extrapolate to $a \to 0$ ("continuum extrapolation")
- sufficiently large L

Core part for quark calculations:

Quark matrix inversion D^{-1}

$$D_{x,y} = \delta_{x,y} - K \sum_{\mu=1}^{4} \left\{ (1-\gamma_\mu) U_{x,\mu} \delta_{x+\mu,y} + (1+\gamma_\mu) U_{y,\mu}^{\dagger} \delta_{x,y+\mu} \right\}$$

(standard Wilson quark)

: large and sparse matrix

$12(L/a)^4 \times 12(L/a)^4 \approx$ 12Mi × 12Mi for a 32^4 lattice.

[12 = 3(color) × 4(Dirac spin)]

condition number $\propto 1/m_q a$

Impossible to simulate ***u*** and ***d*** quarks directly on current computers.

Another extrapolation needed:

- extrapolate to $m_q \to m_{u,d}$ ("chiral extrapolation")

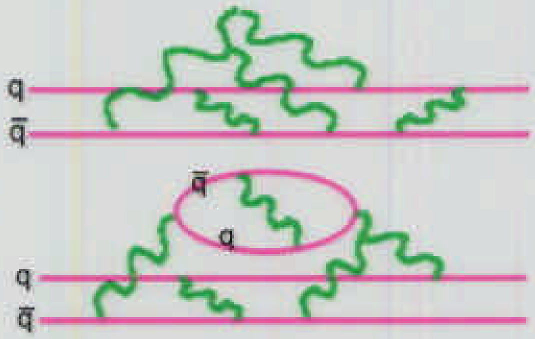
For a good control of these extrapolations,
a systematic study indispensable:
perform all the extrapolations
using
- high-statistic data
- on a sufficiently large lattice
- at several $\boldsymbol{a}$ and $\boldsymbol{m_q}$.

Large computer power required.

⇓

First step: **quenched approximation**

ignore pair-creation/annihilation of sea quarks



⇒ computations < 1/ 100

First systematic study:

GF11 Collaboration *Nucl. Phys. B430 ('94) 179*

$a = 0.07$–0.14 fm (3 lattices), $L \approx 2.4$fm, $m_q \geq 40$MeV ($m_{PS}/m_V \geq 0.5$)

Light hadron spectrum consistent with experiment, to the errors of ≈10%.

- Quality of extrapolations not tested.
- Effects of the quenching not resolved.

Extensive study:

CP-PACS Collab. *PRL 84 ('00) 238*

CP-PACS qQCD simulation

PRL 84 ('00) 238

- gauge action: standard plaquette action
- valence quark: standard Wilson fermion

lattice	β	a [fm]	L_s [fm]	N_{iter}	(N_{sepr})
$32^3\times 56$	5.90	0.102(1)	3.26(3)	160,000	(200)
$40^3\times 70$	6.10	0.078(1)	3.10(3)	240,000	(400)
$48^3\times 84$	6.25	0.064(1)	3.08(3)	420,000	(1000)
$64^3\times 112$	6.47	0.050(1)	3.18(6)	300,000	(2000)

1 iter = 1×HB + 4×OR

	CP-PACS	GF11
lattice spacing: a =	0.05–0.1 fm (4 lattices)	0.07–0.14 (3 lattices)
lattice size: $L \approx$	3 fm ⇒ finite size eff.< 0.5%	2.4 fm
valence quark: $m_q \geq$ $m_{PS}/m_V=$	23MeV 0.75, 0.7, 0.6, 0.5, 0.4	40 MeV ≥ 0.5
statistics: #conf ≈	800	200

about 100 times more floating point computations

Systematic comparison of extrapolation ansätze.
⇒ All extrapolations well under control.

Errors in the light hadron spectrum ≤ 1-3%
(statistical + systematic, except for those from quenching)

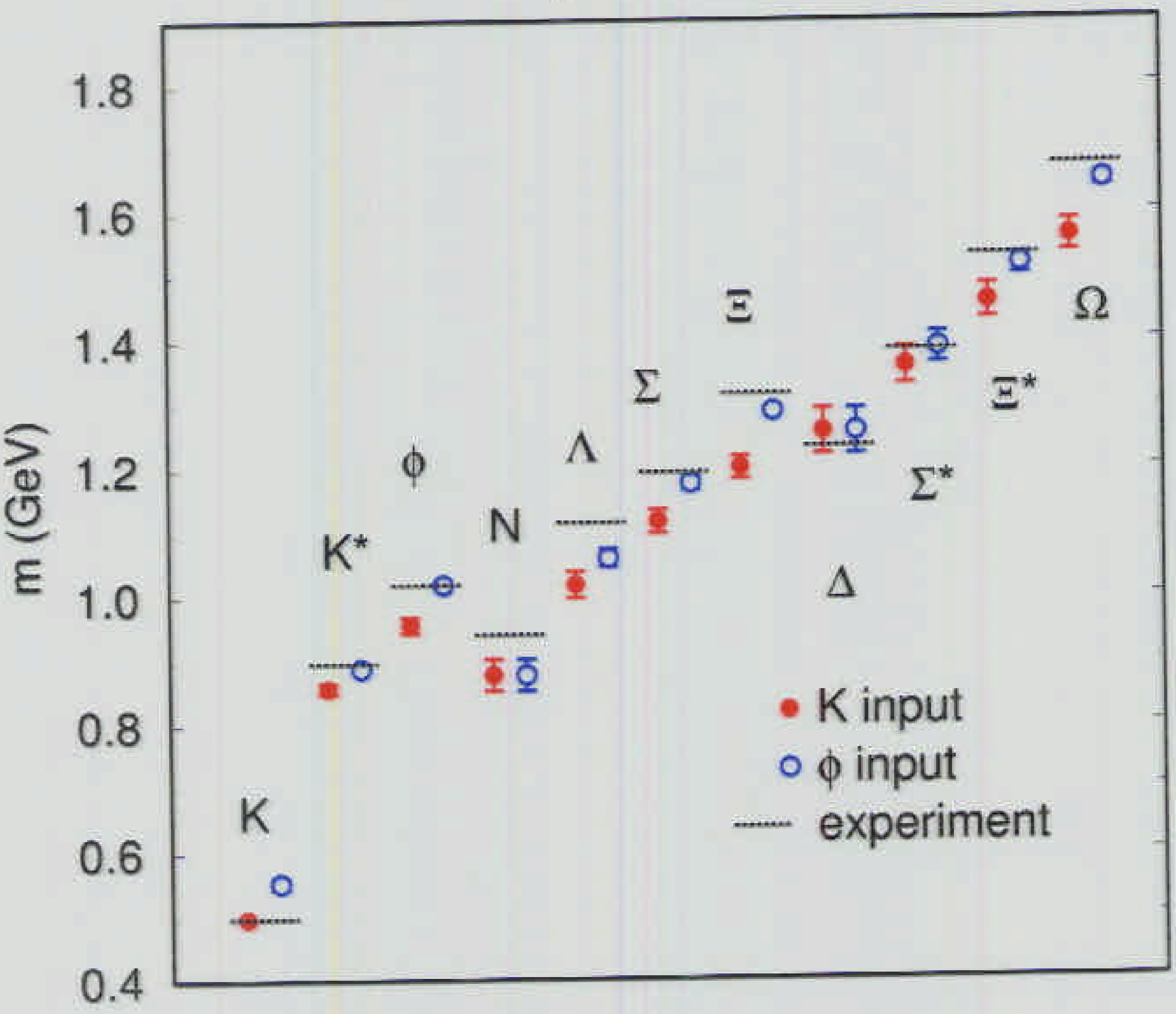
Results:

☆ Hadron spectrum reproduced within O(10)%
➡ QCD is the correct theory of quarks.

☆ Hadron spectrum deviates by ≈10% (7σ)
- ≈10% small K – K* hyperfine splitting
- small decuplet baryon splittings

➡ due to the quenched approximation !
➡ should be removed in full QCD

- $m_u = m_d \equiv m_{ud}$
- M_π , M_ρ $\Rightarrow$ m_{ud} , a
- M_K or M_ϕ $\Rightarrow$ m_s



CP-PACS full QCD simulation

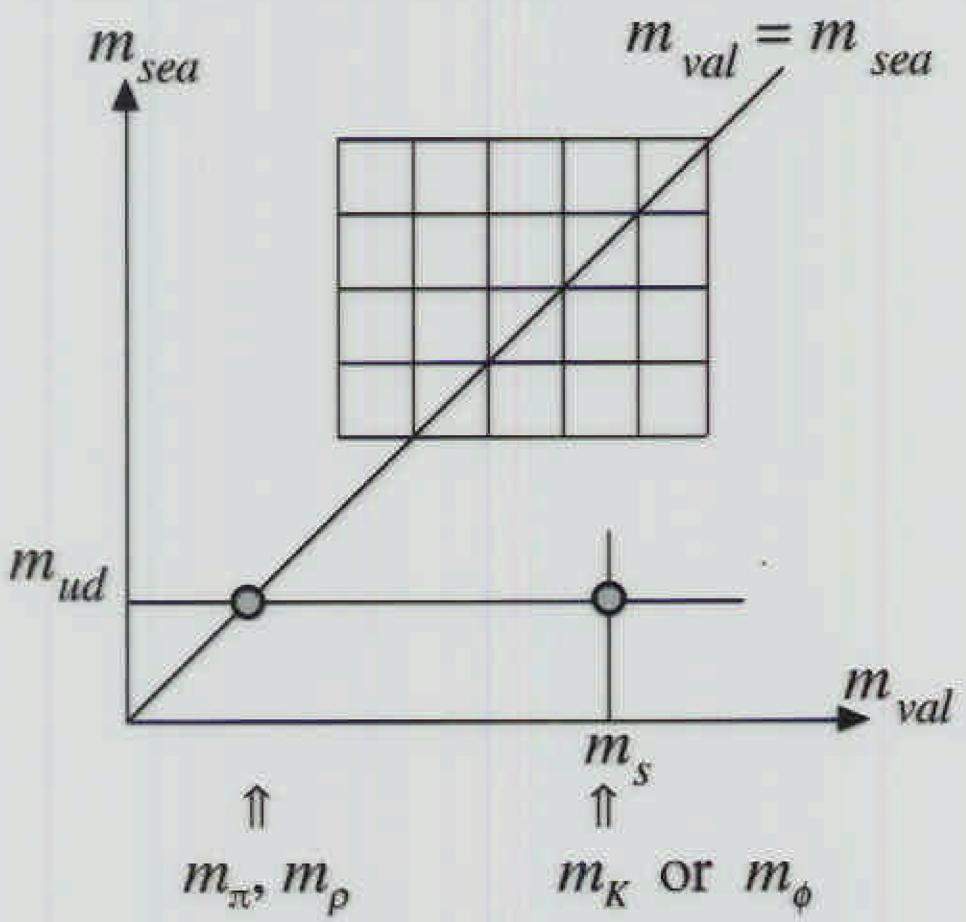
hep-lat/9909045, 9909050, 9909052, 0004010, etc.

N_f=2 full QCD:

partially-quenched QCD

dynamical **u**, **d** (degenerate): *"sea"*
quenched **s**: *"valence"*

(*i*) update with 2 flavors of sea quarks
(*ii*) compute quark propagators at several m_{val}



Large computer power required.

To keep a window for continuum/chiral extrapolations,

⇒ improvement of the lattice theory

s.t. close to the continuum limit
on coarser lattices

- gauge: RG-improved gauge action *Iwasaki ('83)*

$$S_{gauge} = \beta\{c_0 \sum \Box + c_1 \sum \Box\Box\}$$

$\beta = 6/g^2,\ c_1 = -0.331,\ c_0 = 1-8c_1$

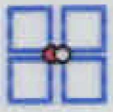
- quark: clover-improved Wilson quark action

Sheikohleslami-Wohlert ('85)

$$S_{quark} = \sum_{f=1,2}\sum_{x,y} \overline{\Psi}_x^f D_{x,y} \Psi_y^f$$

$$D_{xy} = \delta_{xy} - \kappa \sum_\mu \left\{ (1-\gamma_\mu) U_{x\mu} \delta_{x+\mu,y} + (1+\gamma_\mu) U_{y\mu}^\dagger \delta_{x,y+\mu} \right\}$$

$$- \delta_{xy} C_{SW} \kappa \sum_{\mu<\nu} \sigma_{\mu\nu} F_{\mu\nu}(x)$$



MF-improved $C_{SW} = \left\langle \frac{1}{3}\mathrm{Tr}\, U_p \right\rangle^{-3/4}$ with $\left\langle \frac{1}{3}\mathrm{Tr}\, U_p \right\rangle = 1 - 0.8412\beta^{-1}$

A comparative test: *CP-PACS, PR D60 ('99) 114508*

This combination leads to

- good rotational symmetry of static quark pot.

and

- small scaling violation in hadron mass ratios

already from $a \approx 0.2$ fm.

- $a \approx 0.1$–0.2 fm (3 lattices) $\Rightarrow$ continuum extrapolation
- $L \approx 2.5$ fm

lattice	β	a [fm]	L_s [fm]	$N_{trajectory}$
$12^3\times 24$	1.8	0.215(2)	2.58(3)	5000-7000
$16^3\times 32$	1.95	0.153(2)	2.48(3)	5000-7000
$24^3\times 48$	2.1	0.108(1)	2.58(3)	4000*

hadron measurement every 5 trajectories
configuration stored every 10 trajectories
* new (July '00)

- 4 sea quraks $m_{PS}/m_V \approx$ 0.8, 0.75, 0.7, 0.6
- 5 valence quarks 0.8, 0.75, 0.7, 0.6, 0.5

Additional quenched simulation
using the same combination of improved actions
for a direct comparison between full and quenched results,.

1. Light Hadron Spectrum

"To which extent, the discrepancies are removed by dynamical **u, d** quarks?"

Results (qQCD):

☆ Two quenched simulations give universal results in the continuum limit.

Results (fQCD):

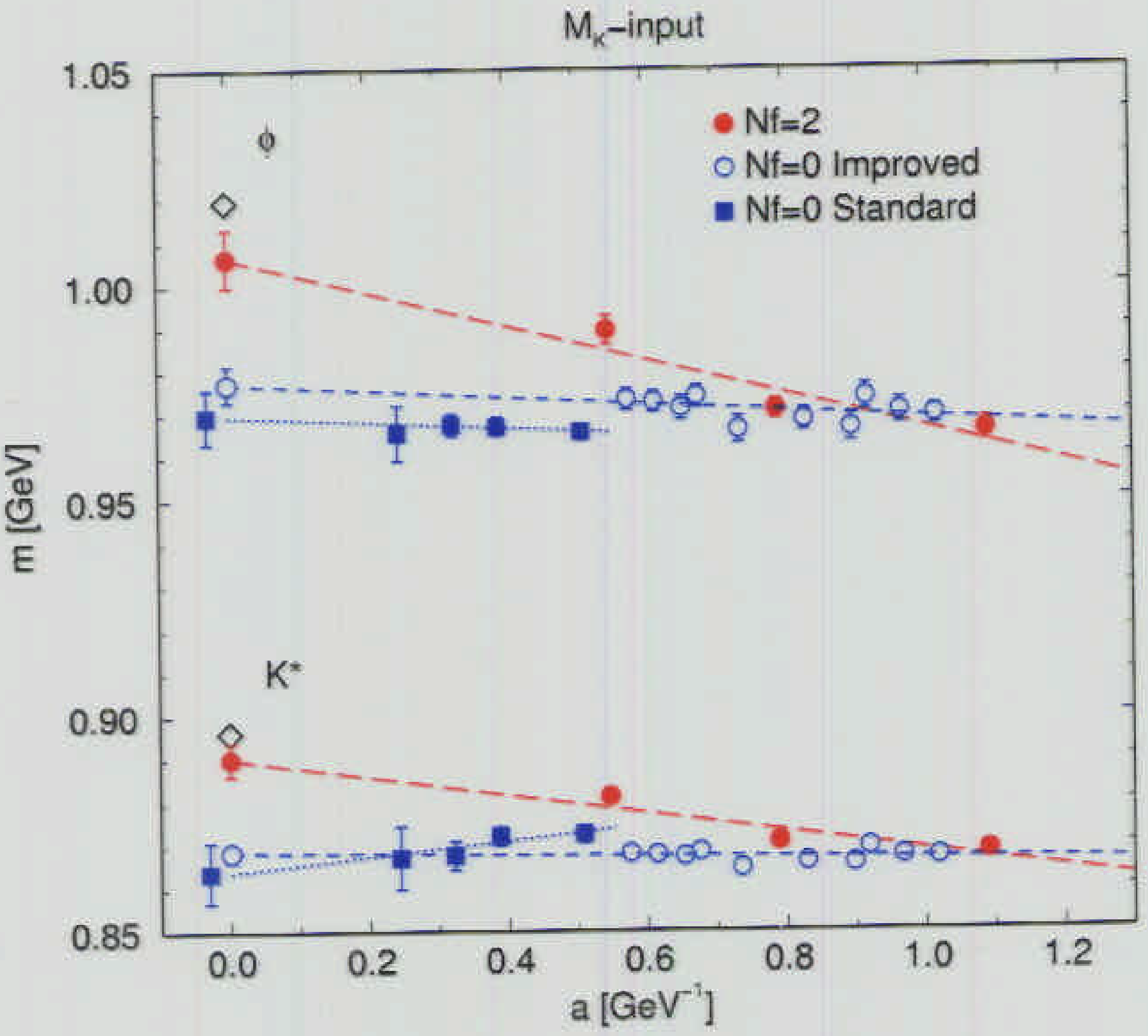
☆ Hadron spectrum much closer to experiment

☆ No big discrepancies between K- and ϕ-input.

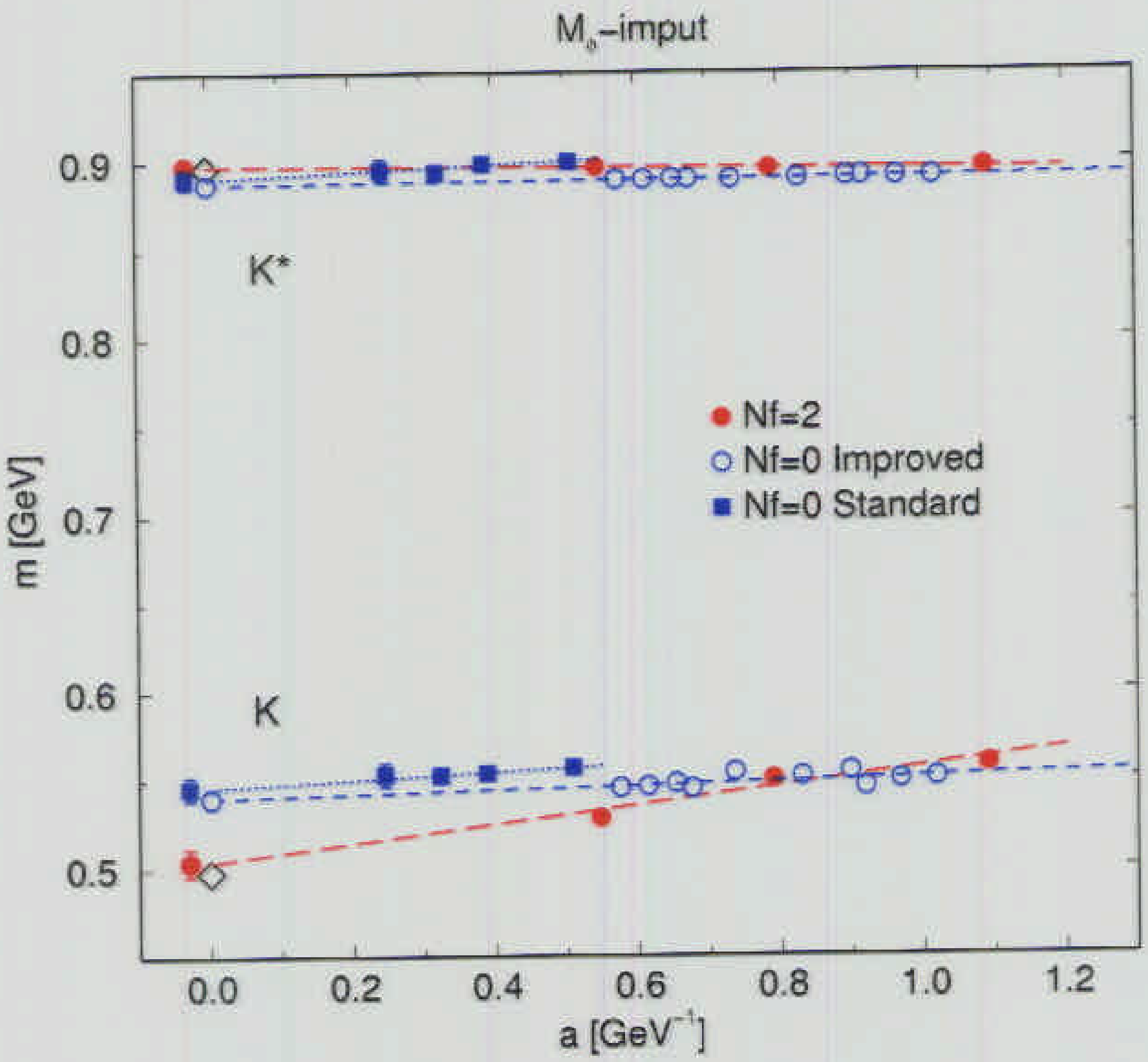
➡ Major quenching artifacts removed.
➡ Importance of dynamical quarks

Possible remaining systematic errors:

- dynamical **s** quark effects
- uncertatines due to the chiral extrapolation
  quenched: $m_{PS}/m_V = 0.4–0.8$
  full QCD: $m_{PS}/m_V = 0.5–0.8$
  influences of $\rho \to \pi\pi$ decay etc.
- uncertatines due to the continuum extrapolation
  only 3 lattices for full QCD
  higher orders in a ??



M_K–input
1.05
1.00
0.95
0.90
0.85
m [GeV]
φ
K*
Nf=2
Nf=0 Improved
Nf=0 Standard
0.0
0.2
0.4
0.6
0.8
1.0
1.2
a [GeV⁻¹]



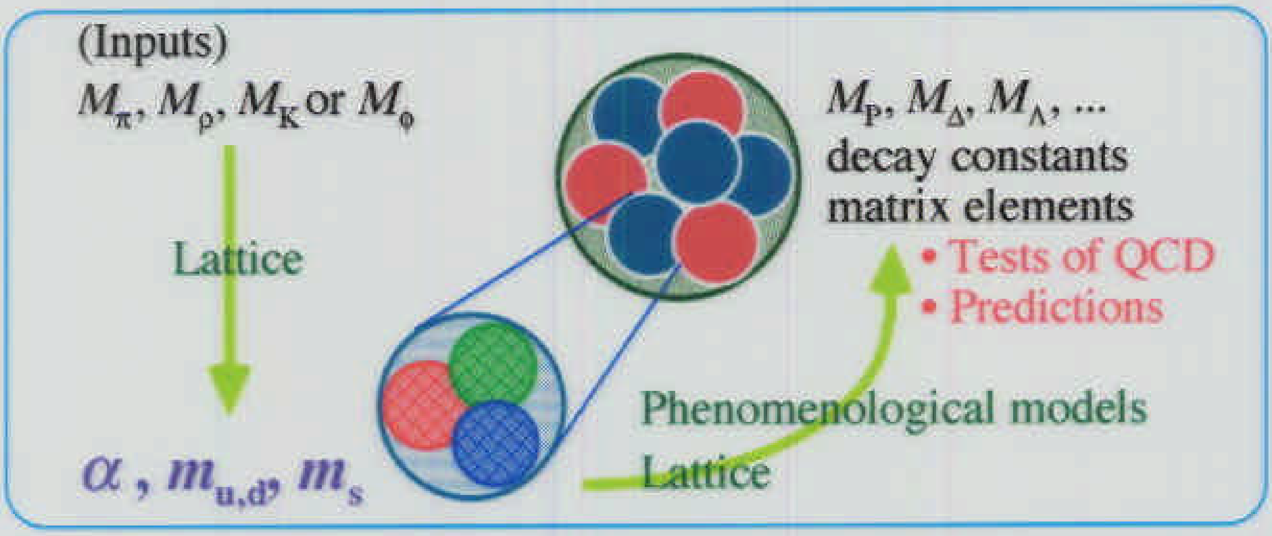
M_ϕ-imput
K*
K
Nf=2
Nf=0 Improved
Nf=0 Standard
m [GeV]
a [GeV^-1]
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2

2. Light Quark Masses

Quarks are **CONFINED** within hadrons.

⇒ No direct experiments for α, m_u, m_d, m_s, ...

Should be determined through a *theoretical* relation between hadronic observables and QCD parameters.



CP-PACS

• Different lattice definitions for m_q

$$m_q^{\mathrm{VWI}} a = Z_m m_q^{bare} a; \quad m_q^{bare} a = 1/2K - 1/2K_c$$

$$m_q^{\mathrm{AWI}} a = \frac{Z_A}{Z_P} \lim_{t\to\infty} \frac{\langle \nabla_4 A_4(t) \cdot P(0) \rangle}{2\langle P(t) \cdot P(0) \rangle}$$

⇒ O(a) difference due to explicit chiral breaking

• O(a)-improvements in the currents: *Lüscher et al., NP B478 ('96)*

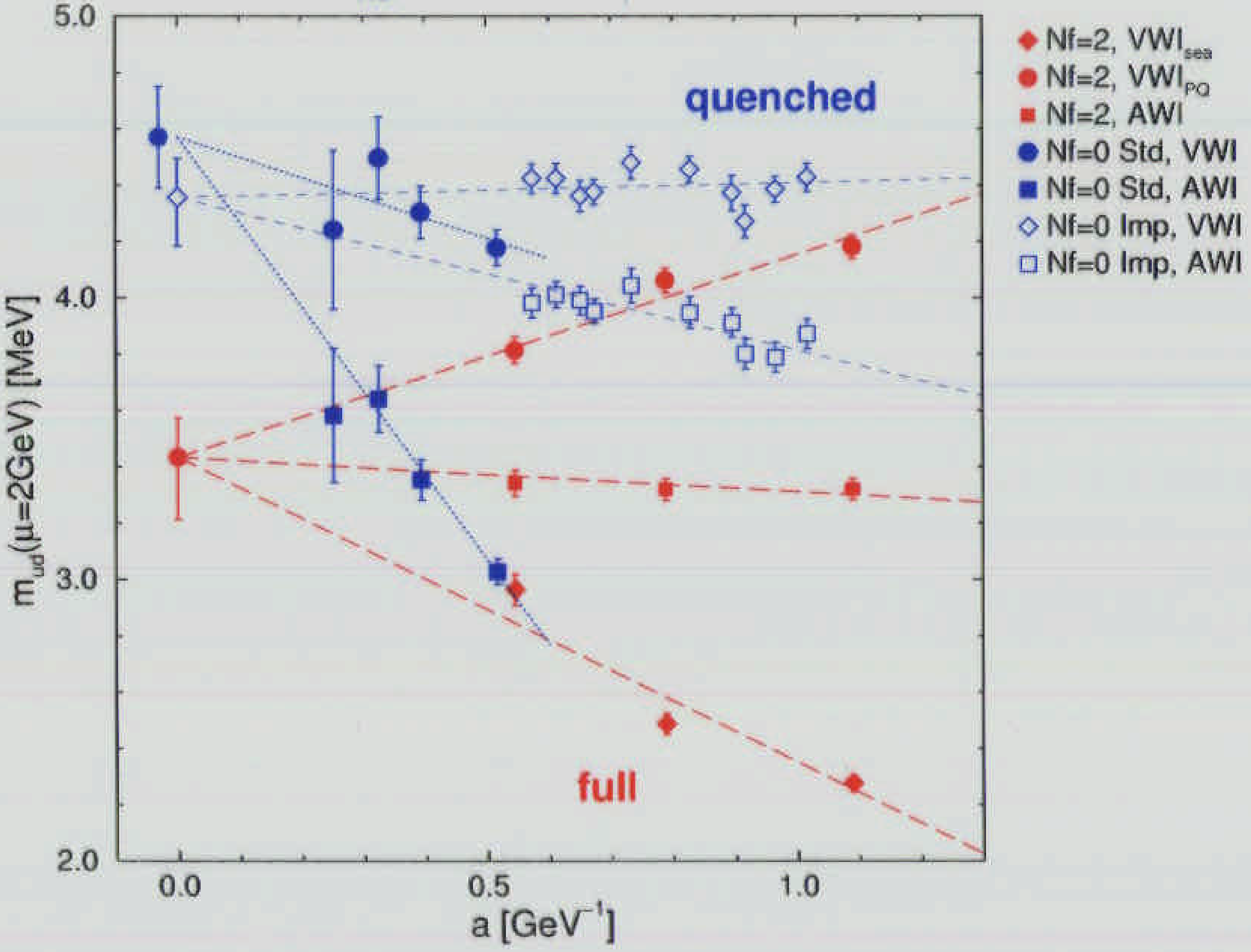
$$A_\mu^R = Z_A\left(1 + b_A m_q^{bare} a\right) \cdot \left\{ A_\mu + c_A \nabla_\mu P \right\}, \text{ etc.}$$

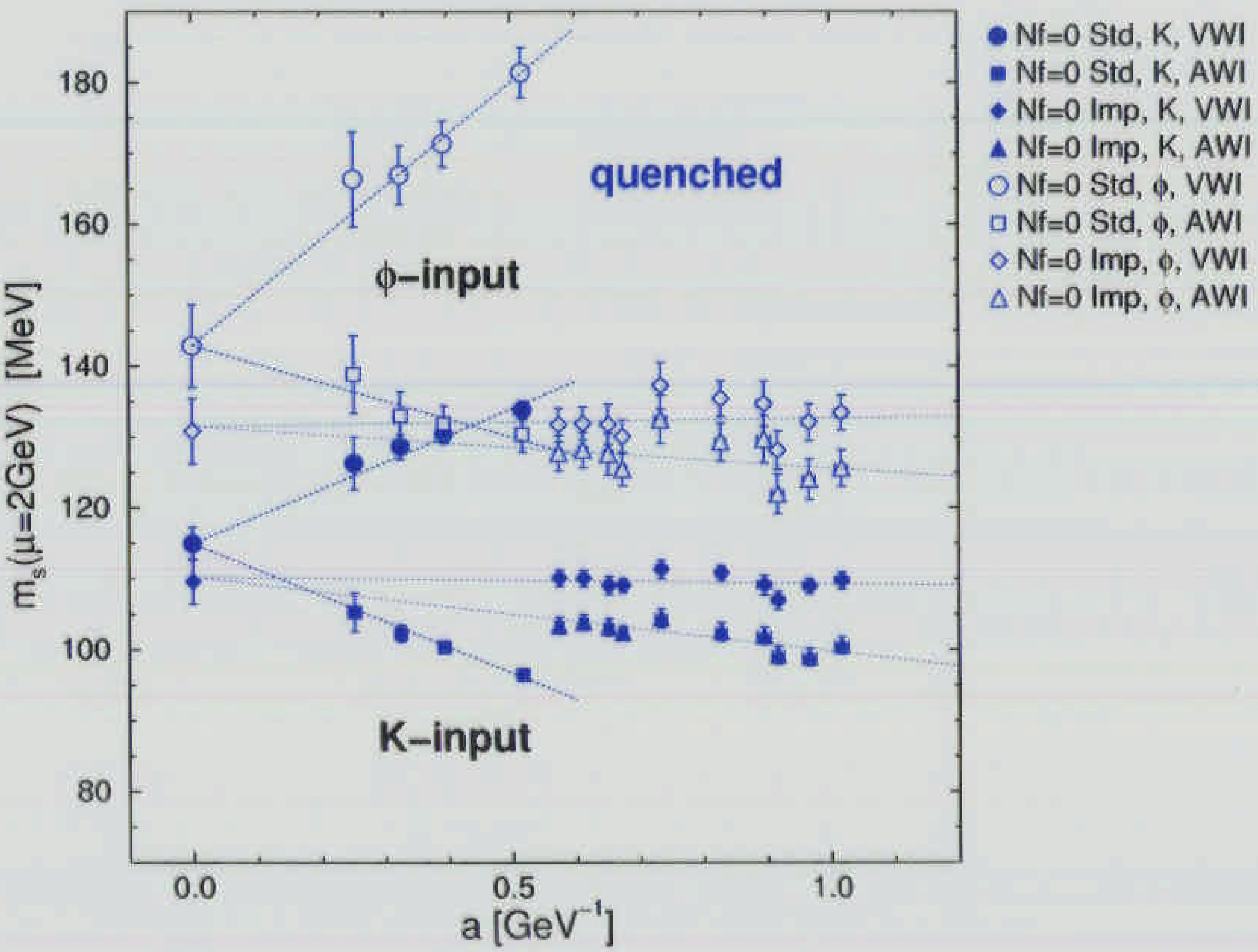
• $Z_{??}$, $b_{??}$, $c_{??}$: 1-loop, usin a MF-improved coupling const.

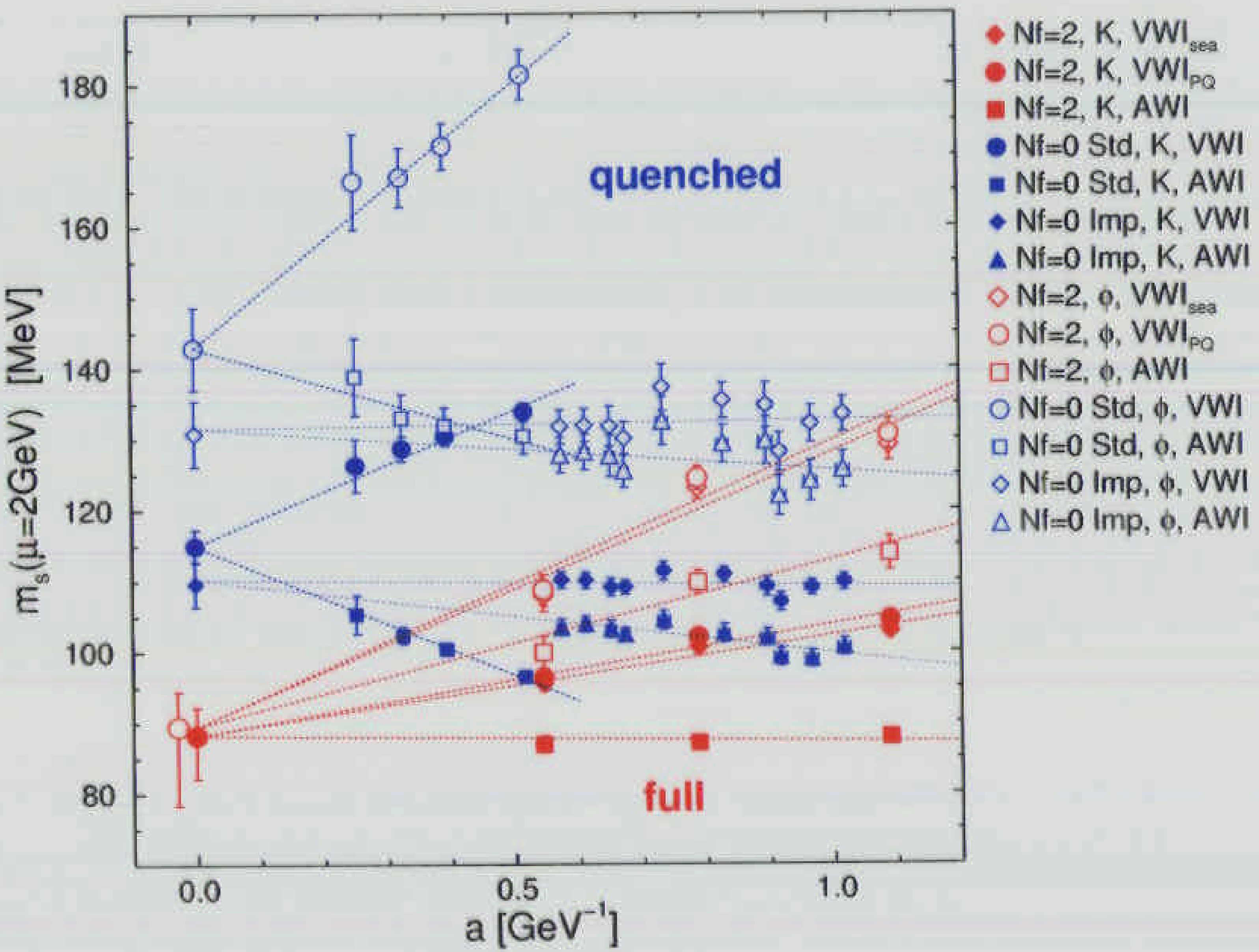
$$g_{\overline{MS}}^{-2}(1/a) = \left(3.648 \cdot W_{1\times1} - 2.648 \cdot W_{1\times2}\right) \cdot g_{Lat}^{-2} - 0.1006 + 0.03149 \cdot N_f$$

with measured Wilson loops extrapolated to the chiral limit.

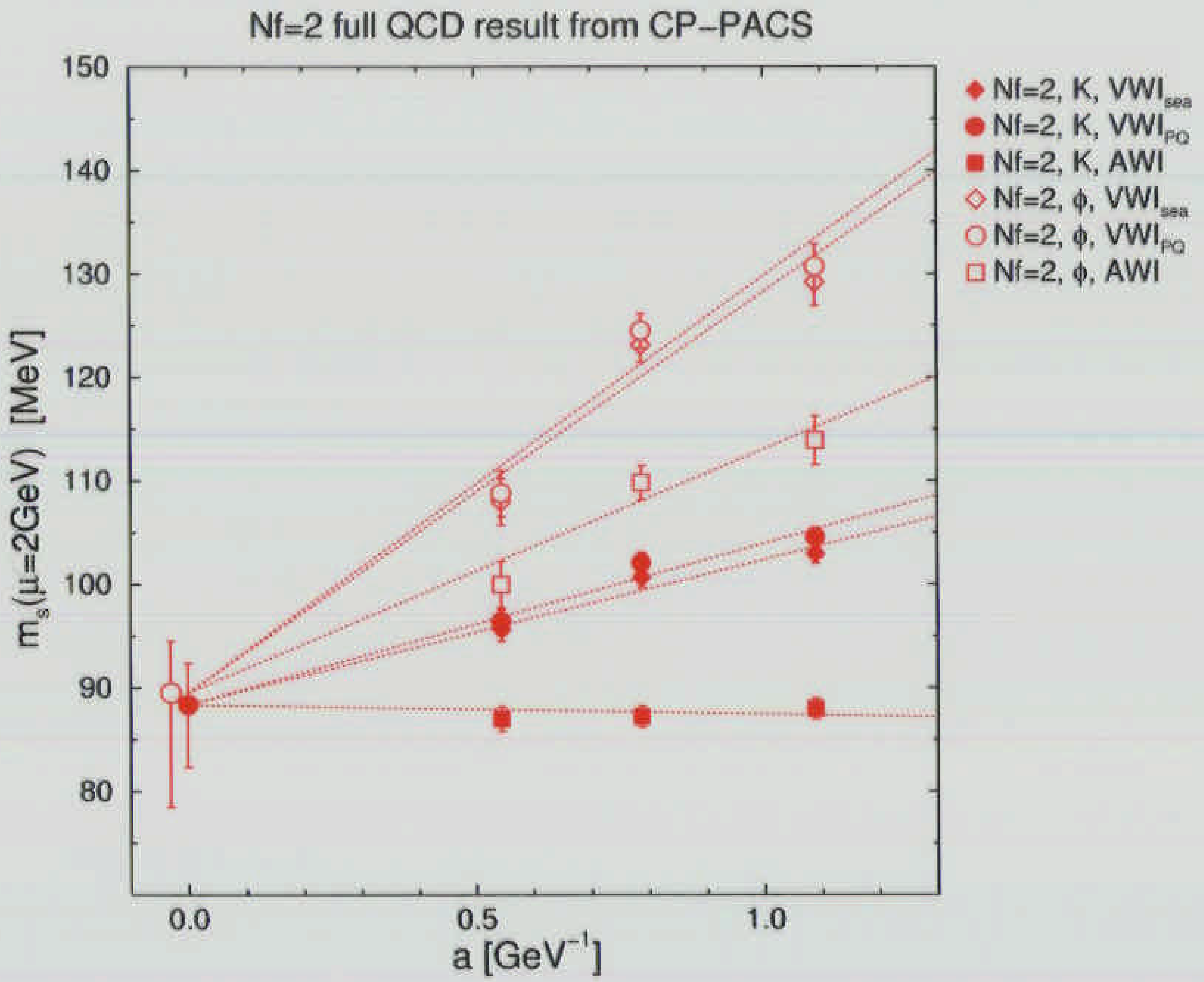
m_{ud} in $\overline{MS}$ ($\mu = 2GeV$)




quenched
φ–input
K–input
180
160
140
120
100
80
0.0
0.5
1.0
$m_s(\mu=2GeV)$ [MeV]
a [GeV^{-1}]
Nf=0 Std, K, VWI
Nf=0 Std, K, AWI
Nf=0 Imp, K, VWI
Nf=0 Imp, K, AWI
Nf=0 Std, φ, VWI
Nf=0 Std, φ, AWI
Nf=0 Imp, φ, VWI
Nf=0 Imp, φ, AWI



quenched
full
180
160
140
120
100
80
$m_s(\mu=2GeV)$ [MeV]
0.0
0.5
1.0
a [GeV^{-1}]
Nf=2, K, VWI_{sea}
Nf=2, K, VWI_{PQ}
Nf=2, K, AWI
Nf=0 Std, K, VWI
Nf=0 Std, K, AWI
Nf=0 Imp, K, VWI
Nf=0 Imp, K, AWI
Nf=2, φ, VWI_{sea}
Nf=2, φ, VWI_{PQ}
Nf=2, φ, AWI
Nf=0 Std, φ, VWI
Nf=0 Std, φ, AWI
Nf=0 Imp, φ, VWI
Nf=0 Imp, φ, AWI



Nf=2 full QCD result from CP-PACS
150
140
130
120
110
100
90
80
$m_s(\mu=2GeV)$ [MeV]
0.0
0.5
1.0
a [GeV^{-1}]
Nf=2, K, VWI_{sea}
Nf=2, K, VWI_{PQ}
Nf=2, K, AWI
Nf=2, ϕ, VWI_{sea}
Nf=2, ϕ, VWI_{PQ}
Nf=2, ϕ, AWI

Results:

(m_q @ 2 GeV in the $\overline{\text{MS}}$-scheme)

☆ Different lattice definitions for m_q

➡ unique value in the continuum limit.

☆ Ambiguity in the choice of input

➡ much reduced in fQCD.

☆ m_q in MeV

input		$N_f=0$ standard	$N_f=0$ improved	$N_f=2$
M_K	$m_s=$	116 ±2	110 +3/−4	88 +4/−6
M_ϕ	$m_s=$	144 ±6	132 +4/−6	90 +5/−11
	$m_{ud}=$	4.57±.18	4.36 +.14/−.17	3.44 +.14/−.22
	$m_s/m_{ud}\approx$	25–31	25–30	26 ± 2

➡ m_q from fQCD: 20–30% smaller than qQCD

- Errors include

	stat.	chiral extrap.	Z-factor	(fQCD) continuum extrap.
m_{ud}	±2.6%	+1.2/-2.3%	+2.3/-5.0%	+1.7/-2.3%
m_s(K)	±2.4%	+1.6/-2.2%	+2.2/-5.6%	+1.4/-2.8%
$m_s(\phi)$	±4.8%	+1.5/-7.6%	+1.7/-6.9%	+0.9/-1.6%

chiral extrap.: different extrapolation formulae
Z-factor: higher orders in pert. theory
⇐ different choices for renormalized g^2 and scale
continuum extrap.: compbined vs. separate extrap.

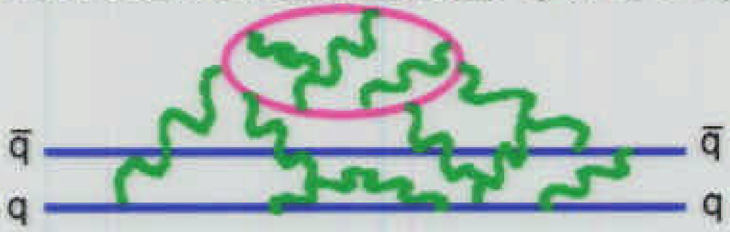
- Comparison with phenomenological models

O(p^4) ChPT: $m_s/m_{ud} = 24.4 \pm 1.5$ Leutwyler, PL B378 ('96)

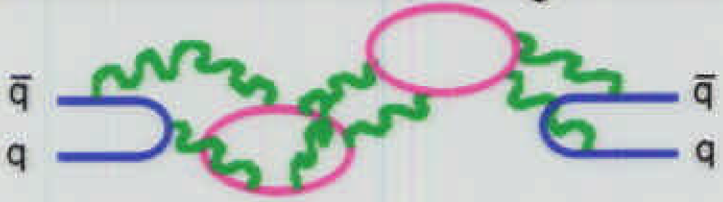
QCD sum rule: $m_s > 90$–100 Narison, hep-ph/9911454
$m_{ud} > 3.5$–4

3. U(1) problem

Propagator for conventional mesons (π, K, etc.):



Additional contribution for flavor-singlet mesons:



Experiment: $M_\eta, M_{\eta'} >> M_\pi$

$\Rightarrow$ The 2nd should cancel the 1st almost completely!

If it is really the case in QCD? "U(1) problem"

- Full QCD simulations essential.
- Computation of the 2nd is not easy:
  requires a special technique and a high statistics.
- Connection with the topological structure of the gauge config.
  through $U(1)_A$-anomaly.

CP-PACS ($N_f = 2$)

First extrapolation to the continuum limit.

- singlet ($u\bar{u}+d\bar{d}$) meson
- ignoring possible mixings with other states
- chiral and continuum extrapolations

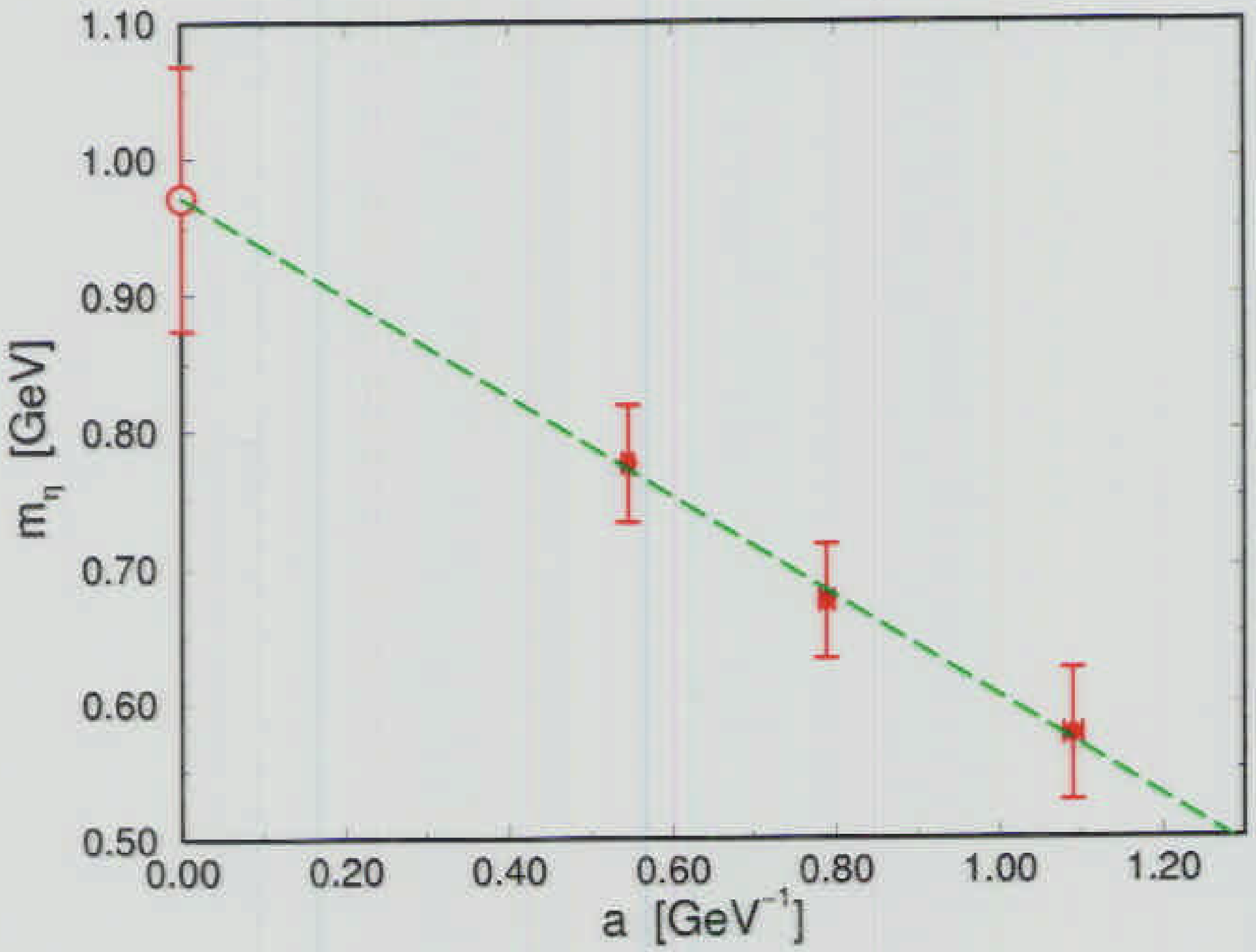
Results:

☆ $M_{(u\bar{u}+d\bar{d})} = 972 \pm 97$ MeV $>> M_\pi = 135$ MeV

- real world $M_\eta = 547$ $\Leftarrow$(mixing)$\Leftarrow$ $u\bar{u}+d\bar{d}$
  $M_{\eta'} = 958$ MeV $s\bar{s}$

Further study of mixing and topology planned.

(cf.) McNeile-Michael, hep-lat/0006020


1.10
1.00
0.90
0.80
0.70
0.60
0.50
m_η [GeV]
0.00
0.20
0.40
0.60
0.80
1.00
1.20
a [GeV^{-1}]

4. B-Physics

f_B, f_{Bs}, B_B, B_{Bs}: important for V_{ts}, V_{td}

Neutral B mass difference $\Delta M_{Bq} \propto f_{Bq}^2 B_{Bq} |V_{tq}|^2$

⇒ *A. Kronfeld* @ ICHEP2000
"B and D mesons in LQCD"

Heavy quarks on the lattice

$m_b a \approx 1$–4 on current lattices ($a^{-1} \approx 1$–3 GeV)
i.e., naive formulations not applicable.

- NRQCD (non-relativistic QCD)
  Lepage et al., PR D46 ('92)
- Relativistic (Fermilab approach)
  El-Khadra, Kronfeld, Mackenzie, PR D55 ('97)

Consistency among different methods should be checked.

B-Physics has been studied mainly in qQCD.

qChPT ⇒ sizable dynamical quarks effects
Booth, PR D51 ('95), Sharpe, Zhang, PR D53 ('96)

Full QCD studies of f_B, f_{Bs}

- **SGO** (Collins et al.), Phys. Rev. D60 ('99)

  NRQCD on configurations with $N_f = 2$ staggered sea quarks
  100 config., $16^3\times32$, β=5.6, $m_q a$=0.01 (m_{PS}/m_V=0.525)

- **MILC** (Bernard et al.), Lattice '99

  relativistic Wilson/Clover
  on configurations with $N_f = 2$ staggered sea quarks
  100–200 config., $16^3\times32$–$24^3\times64$, β=5.5 and 5.6, $m_q a$ =.1–.01

- **CP-PACS**

  NRQCD and relativistic Clover
  on configurations with $N_f = 2$ Clover sea quarks
  and $N_f = 0$ quenched

		$N_f = 0$	$N_f = 2$
f_B	NRQCD	191(5)(11) MeV	204(8)(15) MeV
	relativistic	190(3)(9)	215(11)(11)
f_{Bs}	NRQCD	220(5)(13)	242(9)(17)
	relativistic	224(2)(15)(6)	250(10)(13)(14)
f_{Bs}/f_B	NRQCD	1.150(9)(6)	1.179(18)(7)
	relativistic	1.163(9)(46)(60)	1.186(31)(43)(65)

scale from m_ρ

errors: (stat.+chiral) (syst. from higher orders) [(m_s)]

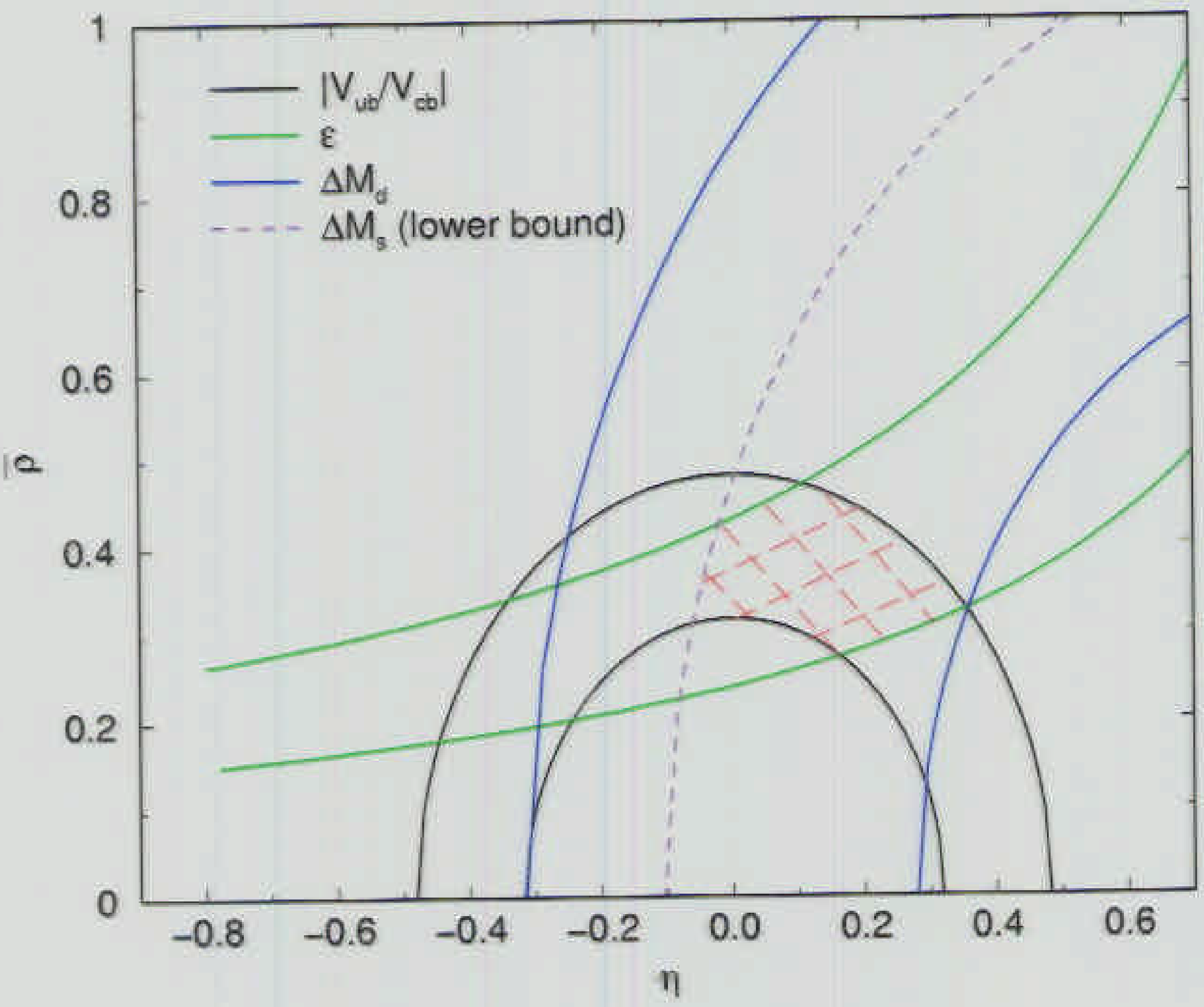
➥ Different methods [redacted] consistent.

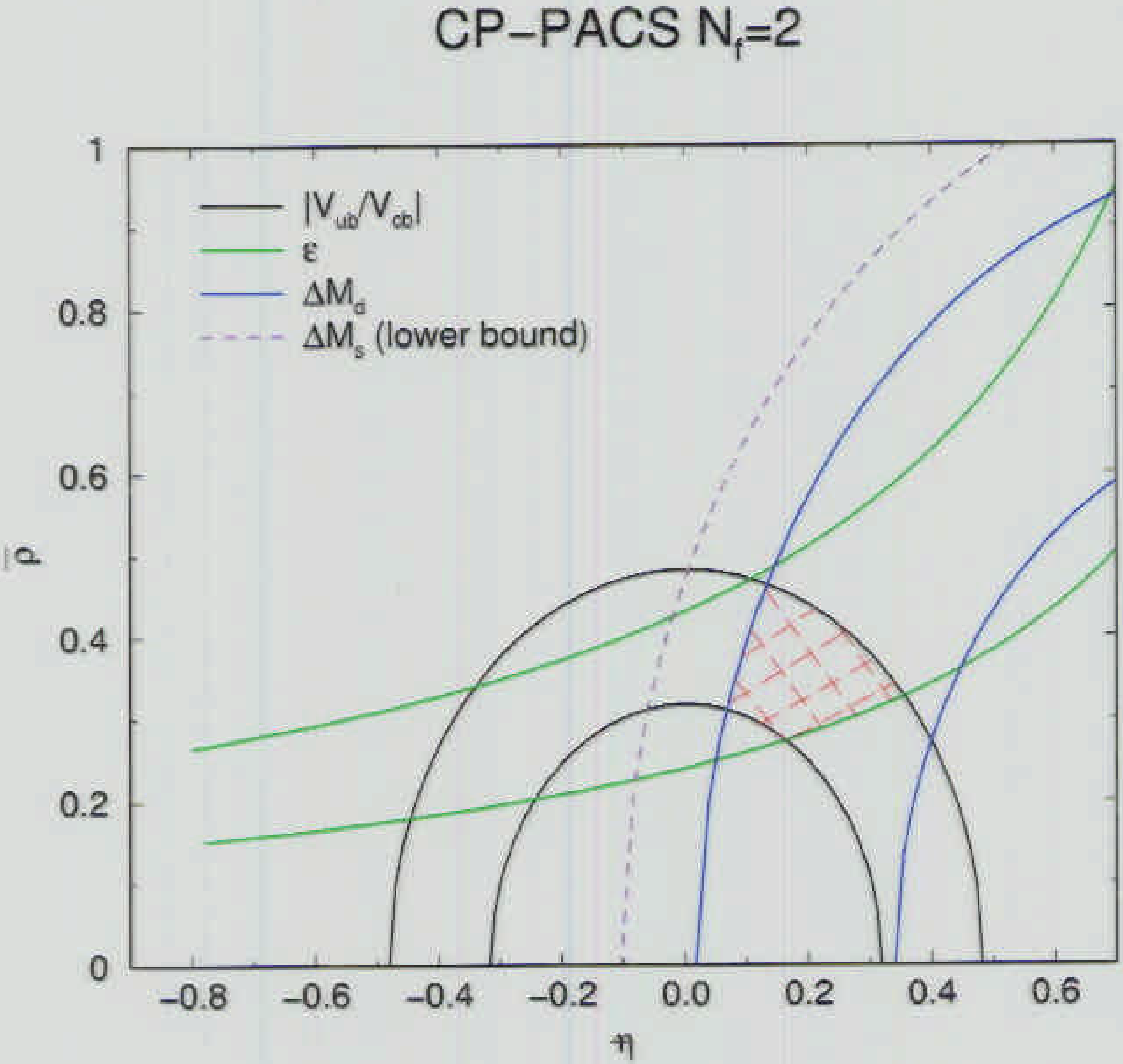
➥ Dynamical quark effects:
f_B, f_{Bs}: ≈10–[redacted]% larger than qQCD
while f_B/f_{Bs}: not sensitive

Need to study yet: B_B, B_{Bs}, form facttors, ...

Standard Inputs

A.J. Buras, hep-ph/9905437





CP−PACS N_f=2
|V_ub/V_cb|
ε
ΔM_d
ΔM_s (lower bound)
1
0.8
0.6
0.4
0.2
0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
ρ̄
η̄

5. Summary

What has been achieved ?

In the quenched approximation:

- qQCD reproduces light hadron spectrum within O(10)%
- Limitation of the quenched approx. made clear

⇩

Full QCD simulations necessary.

First systematic study of N_f=2 full QCD:

- light hadron spectrum close to experiment
  - ➡ Major quenching artifacts removed.
- small quark masses

$$m_{ud} = 3.44 \; {}^{+.14/-.22} \; \text{MeV}$$

$$m_s = 88 \; {}^{+4/-6} \; \text{MeV} \quad M_K\text{-input}$$

$$ 90 \; {}^{+5/-11} \; \text{MeV} \quad M_\phi\text{-input}$$

  - ➡ Impacts for the study of weak interactions.
- U(1) problem, hadronic matrix elements, heavy quark physics, high-T phse transition of QCD, etc
  - ➡ Sizable/noticeable dynamical quark effects.

⇩

Full QCD simulations important.

➩ on-going / to be done:

- smaller quark mass region (decays, ...)
- dynamical strange quark effects
- new chiral fermions (Domain-Wall QCD)