News from the lattice

Laurent Lellouch

CPT Marseille

PASCOS 2009, DESY, Hamburg

(. . . subjective, of course
$\longrightarrow$ many excuses to all whose work is not covered
$\longrightarrow$ complete, detailed overview in yearly Lattice proceedings)

Motivations

- Hadron properties (e.g. masses, widths, structure, etc.) and validation of QCD in nonperturbative domain
- Fundamental QCD parameters (α_s, quark masses)
- Quark-flavor mixing, CP violation and search for new physics

$$\text{Expt.} = (\text{known}) \times (\text{CKM}) \times (\text{long}-\text{distance QCD})$$

- Chiral symmetry breaking (e.g. χPT LEC's) and QCD vacuum
- Finite T and μ QCD
- Nuclear physics from QCD

Motivations

- Strongly coupled gauge theories for dynamical EWSB and BSM physics
- Nonperturbative properties of SUSY gauge theories for dynamical SUSY breaking (also with non-SUSY large-N_c) for exploring AdS/CFT

All above phenomena involve strong interactions which cannot be described w/ an expansion in a small coupling constant

$\Rightarrow$ fully nonperturbative tool required to describe them *in the fundamental theory* w/out uncontrolled approximations

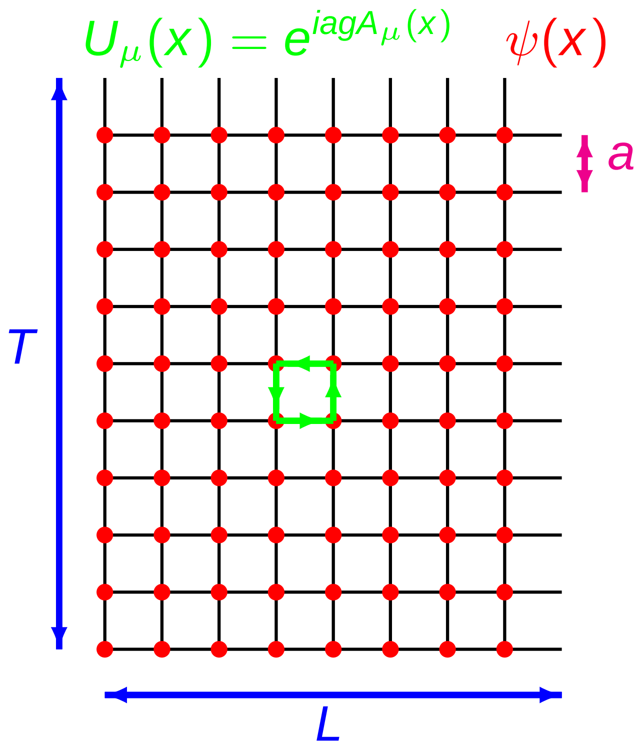
What is Lattice QCD (LQCD)?

Lattice gauge theory $\longrightarrow$ mathematically sound definition of nonperturbative QCD:

- UV (and IR) cutoffs and a well defined path integral in Euclidean spacetime:

$$\langle O \rangle = \int \mathcal{D}U\mathcal{D}\bar{\psi}\mathcal{D}\psi\, e^{-S_G-\int \bar{\psi}D[M]\psi}\, O[U,\psi,\bar{\psi}]$$
$$= \int \mathcal{D}U\, e^{-S_G}\, \det(D[M])\, O[U]_{\text{Wick}}$$

- $\mathcal{D}Ue^{-S_G}\det(D[M]) \geq 0$ and finite # of dof's $\to$ evaluate numerically using stochastic methods



NOT A MODEL: LQCD is QCD when $a \to 0$, $V \to \infty$ and stats $\to \infty$

In practice, limitations ...

Limitations: statistical and systematic errors

In the past: $\det(D[M]) \to \mathrm{cst}$ *(quenching)*; truncation of theory, currently being removed w/ difficult $N_f = 2$ or $2{+}1$ dynamical quark calculations

Limited computer resources $\to$ a, L and m_q are compromises and statistics finite

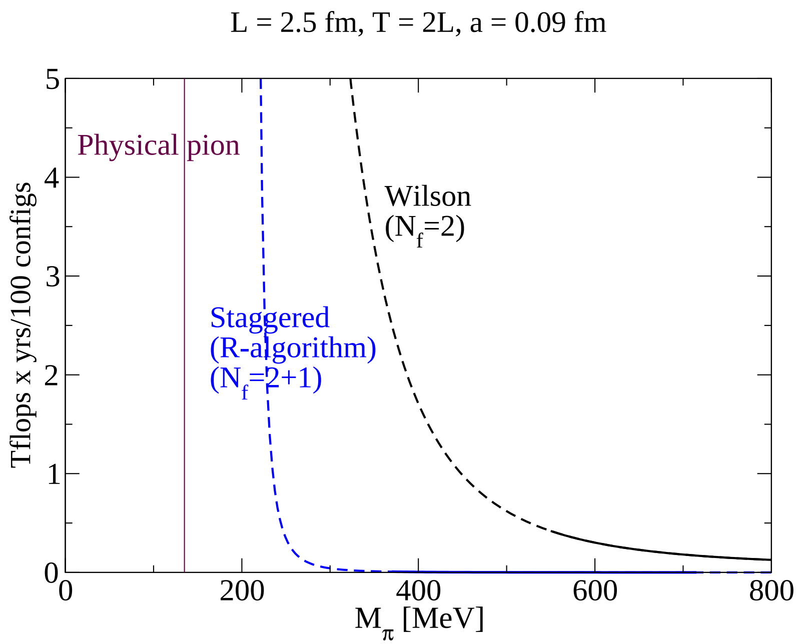
- Statistical: $1/\sqrt{N_{conf}}$; eliminate w/ $N_{conf} \to \infty$
- Discretization: $a\Lambda_{QCD},\ am_q,\ a|\vec{p}|$, with $a^{-1} \sim 2-4\,\mathrm{GeV}$

  $1/m_b < a < 1/m_c \Rightarrow b$ quark cannot be simulated directly
  $\to$ rely on effective theories (large m_Q expansions of QCD)

  Eliminate w/ continuum extrapolation $a \to 0$: need at least three a's
- Chiral extrapolation: m_{ud}^{ph} barely reachable $\Rightarrow m_q[> m_{ud}^{ph}] \to m_{ud}^{ph}$
  Use χPT or regular mass expansions to give functional form
  Requires difficult calculations w/ $M_\pi \lesssim 350\,\mathrm{MeV}$
- Finite volume: for simple quantities $\sim e^{-M_\pi L}$ and $M_\pi L \gtrsim 4$ usually safe
  Resonant states more complicated
  Eliminate with $L \to \infty$ (χPT gives functional form)
- Renormalization: like in all field theories, must renormalize;
  can be done in PT, best done nonperturbatively

The Berlin wall ca. 2001

Unquenched calculations very demanding: # of d.o.f. $\sim \mathcal{O}(10^9)$ and large overhead for computing $\det(D[M])$ ($\sim 10^9 \times 10^9$ matrix) increased more rapidly than expected as $m_{u,d} \longrightarrow m_{u,d}^{ph}$



Staggered and Wilson with traditional unquenched algorithms ($\leq$ 2004)

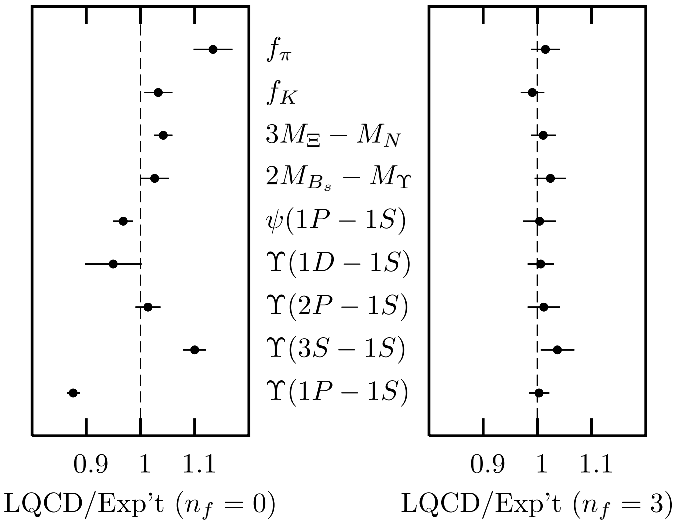
- cost $\sim N_{\rm conf} V^{1\rightarrow 5/4} M_\pi^{-(5\rightarrow 6)} a^{-7}$ (Gottlieb '02, Ukawa '02)
- Here, staggered $M_\pi \simeq \langle M_\pi \rangle^{\rm RMS}_{\rm taste}$
- Both formulations have a cost wall
- Wall appears for lighter quarks w/ staggered

$\longrightarrow$ MILC got a head start w/ staggered fermions: $N_f = 2+1$ simulations with $\langle M_\pi \rangle^{\rm RMS}_{\rm taste} \gtrsim 310\,\rm MeV$

- Impressive effort: many quantities studied
- Detailed study of chiral extrapolation with staggered χPT (SχPT)

2001 – 2006: staggering dominance

Staggered fermions reign



(Davies et al '04)

Devil's advocate! $\longrightarrow$ potential problems:

- $\det[D_{N_f=1}] \simeq \det[D_{\rm stag}]^{1/4}$ to eliminate spurious "tastes" w/ $D_{\rm stag} = D_{N_f=1} \otimes \mathbb{I}_4 + a\Delta$:

$$\det[D_{\rm stag}]^{1/4} = \det\Big[\mathrm{diag}\{D_{N_f=1}, 1, 1, 1\}$$
$$+\frac{a}{4}\mathrm{diag}\{1, D^{-1}_{N_f=1}, D^{-1}_{N_f=1}, D^{-1}_{N_f=1}\}\Delta + O(a^2)\Big]$$

  $\Rightarrow$ non-local theory, studied by Shamir, Bernard, Golterman, Sharpe, Creutz '04-'08
  $\Rightarrow$ QCD when $a \to 0$? (Universality?)

- at larger a, significant lattice artefacts
  $\Rightarrow$ complicated chiral extrapolations w/ SχPT

- review of staggered issues in Sharpe '06, Kronfeld '07, Golterman '08

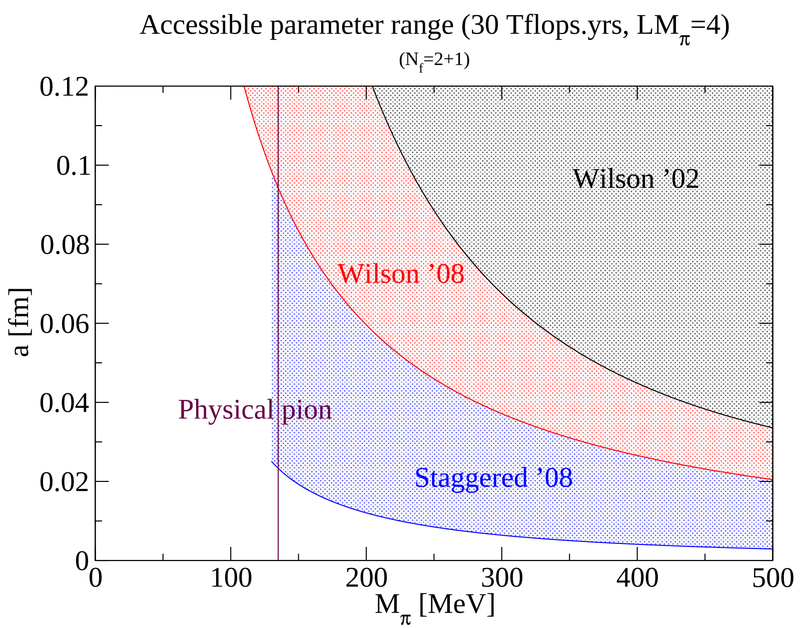
$\Rightarrow$ Important to have alternative approaches which stand on firmer theoretical ground

The fall of the Berlin wall

Better understanding of the dynamics of the simulations

→ algorithmic improvements: Schwarz-preconditioned Hybrid Monte Carlo (Lüscher '03-'04, PACS-CS '08); HMC algorithm with multiple time scale integration and mass preconditioning (Sexton et al '92, Hasenbusch '01, Urbach et al '06, BMW '07); Deflation acceleration for LQCD (Lüscher '07)

→ better choice of simulation parameters



- Tremendous gains in numerical cost (Del Debbio et al '07, Ukawa '08, Sugar '08)
  - prefactor → prefactor$/5 \cdot 10^2$
  - $M_\pi^6 \to M_\pi^2$
  - $a^{-7} \to a^{-6}$
- Tremendous increase in computer power: Pflops computers are becoming available (often based on LQCD machines)
- Parameter range obtained assuming 30 Tflops.yrs available w/ $LM_\pi = 4$ kept fix

→ very soon, LQCD calculations with $N_f = 2 + 1$ improved Wilson fermions at *physical* m_{ud}, with $a \simeq 0.09\,\mathrm{fm}$ and $L \simeq 6\,\mathrm{fm}$

→ physical QCD is getting within reach (for many observables)

Ab initio calculation of light hadron masses

Dürr, Fodor, Frison, Hoelbling, Hoffman, Katz, Krieg, Kurth, Lellouch, Lippert, Szabo, Vulvert (BMW) Science 322 '08

Aim: determine the light hadron spectrum in QCD in a calculation in which all sources of systematic errors are controlled to within a few%

- $\Rightarrow$ inclusion of $N_f = 2 + 1$ sea quark effects w/ improved Wilson fermions
- $\Rightarrow$ systematic treatement of unstable particles (Lüscher '85-'91)
- $\Rightarrow$ large volumes–up to $(4\,\mathrm{fm})^3$– to guarantee negligible finite-size effects which are nevertheless quantified
- $\Rightarrow$ controlled interpolations to m_s^{ph} (straightforward) and extrapolations to m_{ud}^{ph} (difficult) with $M_\pi \gtrsim 190\,\mathrm{MeV}$
- $\Rightarrow$ controlled extrapolations to continuum limit with 3 $a \simeq 0.065, 0.085, 0.125\,\mathrm{fm}$
- $\Rightarrow$ 2×432 different procedures and statistical resampling combined in a "blind" analysis

Simulation parameters

β, a [fm]	am_{ud}	M_π [GeV]	am_s	$L^3 \times T$	# traj.
3.3	-0.0960	0.65	-0.057	$16^3 \times 32$	10000
	-0.1100	0.51	-0.057	$16^3 \times 32$	1450
$\sim$ 0.125	-0.1200	0.39	-0.057	$16^3 \times 64$	4500
	-0.1233	0.33	-0.057	$16^3 \times 64$ | $24^3 \times 64$ | $32^3 \times 64$	5000 | 2000 | 1300
	-0.1265	0.27	-0.057	$24^3 \times 64$	700
3.57	-0.03175	0.51	0.0	$24^3 \times 64$	1650
	-0.03175	0.51	-0.01	$24^3 \times 64$	1650
$\sim$ 0.085	-0.03803	0.42	0.0	$24^3 \times 64$	1350
	-0.03803	0.41	-0.01	$24^3 \times 64$	1550
	-0.044	0.31	0.0	$32^3 \times 64$	1000
	-0.044	0.31	-0.07	$32^3 \times 64$	1000
	-0.0483	0.20	0.0	$48^3 \times 64$	500
	-0.0483	0.19	-0.07	$48^3 \times 64$	1000
3.7	-0.007	0.65	0.0	$32^3 \times 96$	1100
	-0.013	0.56	0.0	$32^3 \times 96$	1450
$\sim$ 0.065	-0.02	0.43	0.0	$32^3 \times 96$	2050
	-0.022	0.39	0.0	$32^3 \times 96$	1350
	-0.025	0.31	0.0	$40^3 \times 96$	1450

- # of trajectories given is after thermalization
- autocorrelation times (plaquette, n_{CG}) less than $\approx$ 10 trajectories
- 2 runs with 10000 and 4500 trajectories $\longrightarrow$ no long-range correlations found

QCD parameters and light hadrons

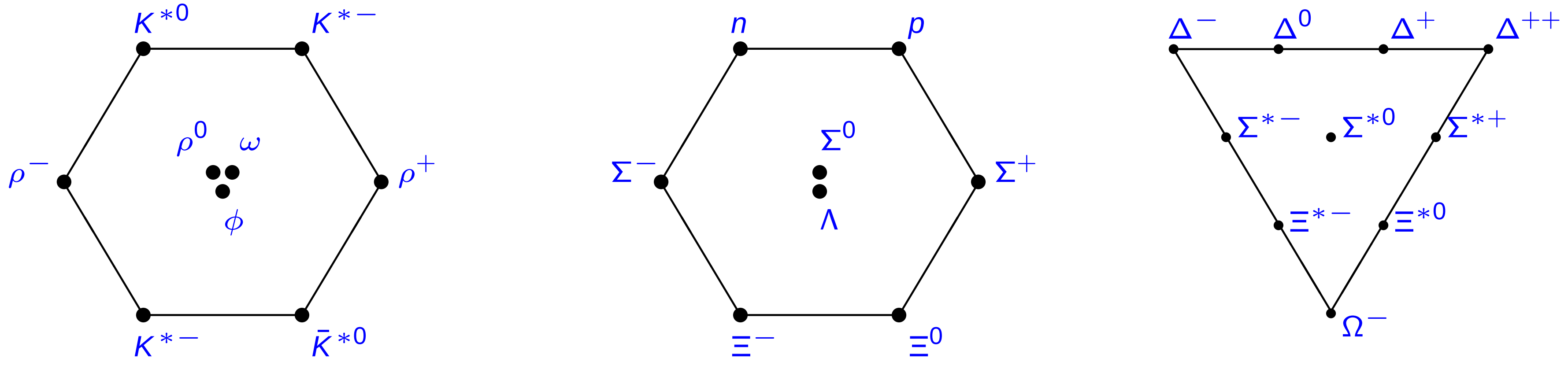
$N_f=2+1$ QCD (isospin limit) has 3 parameters which have to be fixed w/ expt:

- $\Lambda_{\rm QCD}$: fixed w/ Ω or Ξ mass
  - don't decay through the strong interaction
  - have good signal
  - have a weak dependence on m_{ud}

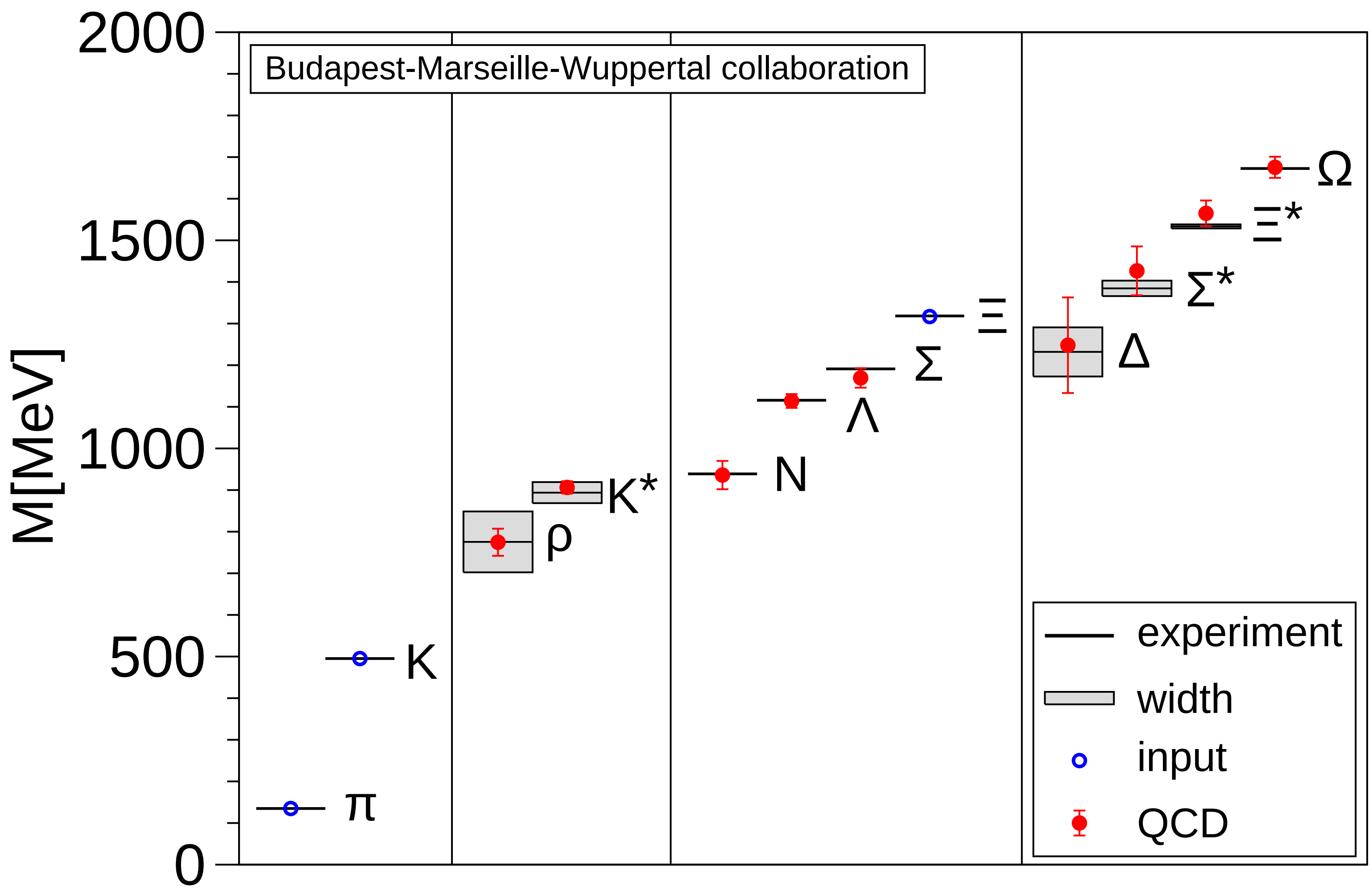
  $\longrightarrow$ 2 separate analyses and compare

- (m_{ud}, m_s): fixed using M_π and M_K

Determine masses of remaining non-singlet light hadrons in



Post-dictions for the light hadron spectrum



(see also partial calculations from MILC '04-'09, QCDSF '07, ETM '08, Walker-Loud et al '08, PACS-CS '08, NPLQCD '09)

Our “particle accelerators”

IBM Blue Gene/L (JUBL), FZ Jülich
45.8 Tflop/s peak

IBM Blue Gene/P (JUGENE), FZ Jülich
223 Tflop/s peak

IBM Blue Gene/P (Babel), IDRIS Paris
139 Tflop/s peak

And computer clusters at Uni. Wuppertal and CPT Marseille

A parte: Flavianet Lattice Averaging Group (FLAG)

- Working group of EU network “Flavianet”: G. Colangelo, S. Dürr, A. Jüttner, LL, H. Leutwyler, V. Lubicz, S. Necco, C. Sachrajda, S. Simula, A. Vladikas, U. Wenger, H. Wittig
- Aim: provide a critical review and summary of Lattice QCD results relevant for phenomenology and accessible to non-experts
- Work in progress

  $\Rightarrow$ will make use of some of the material already gathered . . .

  . . . but bear sole responsibility for its misuse
- Method used for combining results described in LL ’09

Light quark masses

Fundamental parameters of SM:

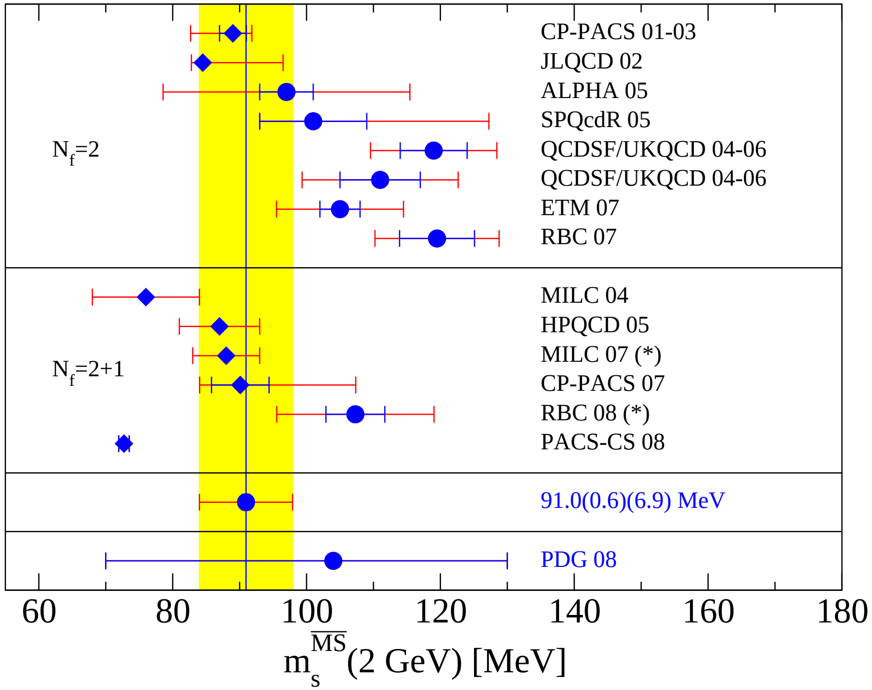
- $m_u, m_d \ll \Lambda_{QCD}$ → very light, $m_s \lesssim \Lambda_{QCD}$ → lightish
- values of $m_u, m_d(, m_s)$ are responsible for the variety of atoms in nature
- precise values improve phenomenology (m_s) and constraints on GUTs
- difficult to measure: $u, d(, s)$ are confined in hadrons w/ $M_{had} \gg m_{u,d(,s)}$

Lattice calculations to date

- performed in isospin limit $(m_u - m_d)/\Lambda_{QCD} \to 0$: obtain $m_{ud} \equiv (m_u + m_d)/2$
- m_{ud} by *extrapolation* (from $m_{ud} \sim 3m_{ud}^{ph}$), m_s by *interpolation*
- need 3 observables:
  - 1 to fix Λ_{QCD} (e.g. a stable hadron mass)
  - 1 to fix $m_{ud} \to M_\pi$
  - 1 to fix $m_s \to M_K$

→ bare lagrangian parameters
$\Rightarrow$ must renormalize; best to do nonperturbatively
→ difficult to control at percent level

strange quark mass: unquenched summary



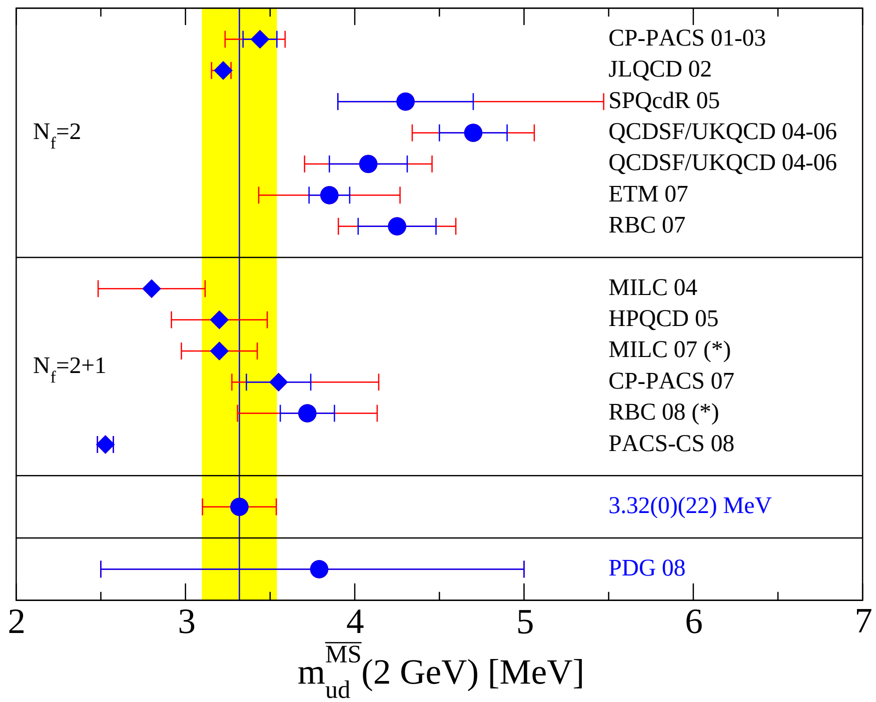
- perturbatively renormalized results systematically lower than nonperturbatively renormalized ones ($\chi^2/dof = 2.3$ for (*) fit)
- effect dominates over $N_f = 2 \to 2+1$
- 14% (1.4σ) increase in going from 1-loop to 2-loop perturbative renormalization (MILC '04 $\to$ HPQCD '05)
- average dominated by MILC '07

  $\Rightarrow$ may suffer from underestimated renormalization uncertainty
- $\delta m_s = 8\%$ is aggressive

  $\Rightarrow$ use w/ caution

  $\Rightarrow$ need fully controlled independent calculations
- average is close to saturating dispersive bounds (e.g. LL et al '97)

average up-down quark mass: unquenched summary



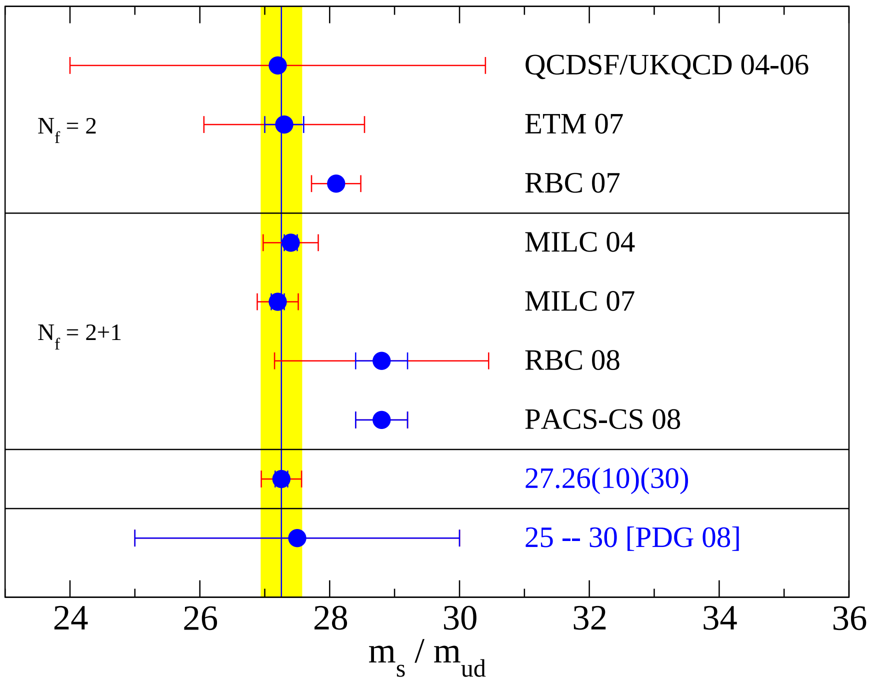
- similar discrepancy between perturbatively and nonperturbatively renormalized results, though a bit marred by chiral extrapolation
- same 1-loop to 2-loop jump
- average still dominated by MILC '07

  ⇒ may again suffer from underestimated renormalization errror
- $\delta m_{ud} = 7\%$ is even more aggressive, given extra extrapolation necessary

  ⇒ use w/ even more caution

  ⇒ need fully controlled independent calculations
- average is close to saturating dispersive bounds (e.g. LL et al '97)

m_s/m_{ud}: unquenched summary



- renormalization cancels here!
- outliers may have problems w/ chiral extrapolation (RBC '08) or finite-volume effects (PACS-CS '08)
- $\delta(m_s/m_{ud}) = 1\%$
- result corresponds to a $\sim$ 5% correction to LO current algebra prediction

$|V_{us}|$ from experiment and the lattice

Precision tests of CKM unitarity/quark-lepton universality and constraints on NP from

$$\frac{G_q^2}{G_\mu^2}\left[|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2\right]=\left[1+O\left(\frac{M_W^2}{\Lambda_{NP}^2}\right)\right]$$

- $|V_{ud}| = 0.97425(22)$ [0.02%] from nuclear β decays (Hardy & Towner '08)
  $\Rightarrow \delta|V_{ud}|^2 = 4.3\cdot 10^{-4}$
- $|V_{ub}| = 3.87(47)\cdot 10^{-3}$ [12%] (CKMfitter '09)
  $\Rightarrow |V_{ub}|^2 \simeq 1.5\cdot 10^{-5}$

Since $|V_{us}|\simeq 0.225$, need $\delta|V_{us}|\sim 0.5\%$ to match contribution of $\delta|V_{ud}|$ to unitarity sum

$|V_{us}|$ is best determined from $K\to\pi\ell\nu$ and $K\to\mu\bar{\nu}(\gamma)$

Large amounts of new data: BNL-E865, KLOE, KTEV, ISTRA+, NA48

$|V_{us}|$ from $K \to \pi\ell\nu$

Measurement of $|V_{us}|$ requires theoretical determination of $f_+(q^2)$:

$$\langle\pi^+(p')|\bar{u}\gamma_\mu s|\bar{K}^0(p)\rangle \longrightarrow f_+(q^2),\ f_0(q^2) \qquad q = p - p'$$

$\Rightarrow$ form factor shape measured in experiment and extract (Flavianet '07)

$$|V_{us}| \times f_+(0) = 0.21664(48)\ [0.22\%]$$

Theoretical framework: ChPT (Leutwyler & Roos '84, Gasser & Leutwyler '85)

$$f_+(0) = 1 + f_2 + f_4 + \cdots$$

Ademollo-Gatto thm and χPT: $f_2 = O\left(\frac{(M_K^2 - M_\pi^2)^2}{M_K^2\Lambda_\chi^2}\right) = -0.023$, fully determined in terms of M_K, M_π and F_π!

$\Rightarrow$ need a reliable nonperturbative calculation of

$$\Delta f \equiv f_+(0) - 1 - f_2 = O\left(\frac{(M_K^2 - M_\pi^2)^2}{\Lambda_\chi^4}\right) \sim 3\%$$

$|V_{us}|$ from $K \to \pi\ell\nu$

On lattice, actually calculate $f_+(0) - 1$

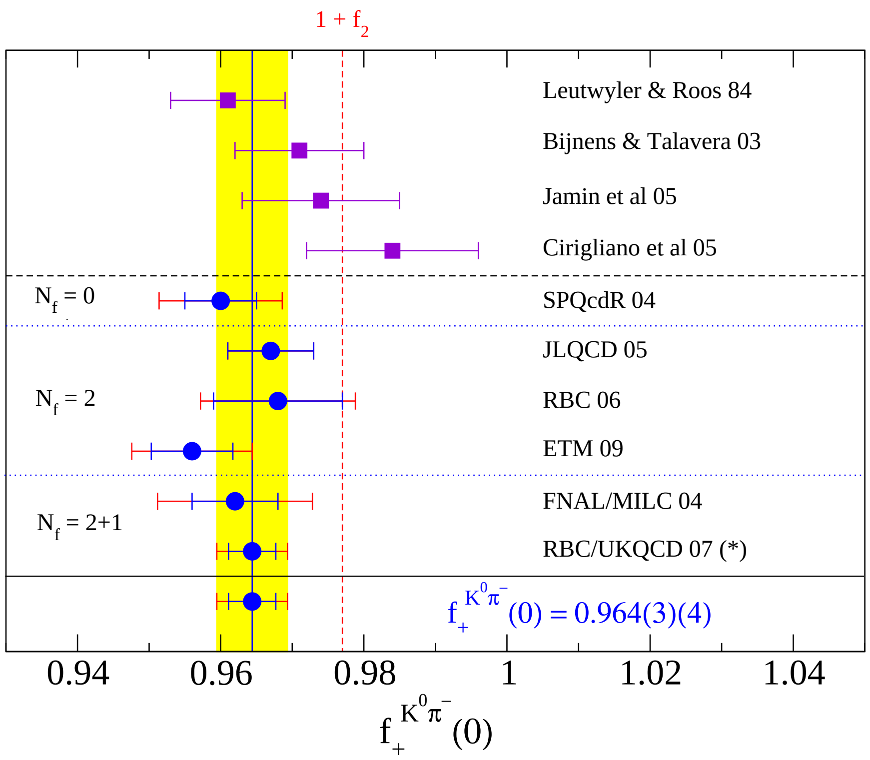
Need $f_+(0) - 1$ to:

- $\sim 10\%$ to match $\delta|V_{ud}|$ contribution to unitarity sum
- $\sim 6\%$ to match experimental error in $K \to \pi\ell\nu$

Many non-lattice calculations of f_4:

- NNLO logs computed (Post & Schilcher '02, Bijnens & Talavera '03)
- requires $O(p^6)$ LECs; estimates in Bijnens & Talavera '03, Jamin et al '04, Cirigliano et al '05, Portoles '07
- $O(p^6)$ LECs can be determined from slope and curvature of $f_+(q^2)$ (Bijnens & Talavera '03)
- Reference result (Leutwyler & Roos '85): $\Delta f = -0.016(8)$

$f_+(0)$ from the lattice: summary



- $\delta f_+(0)^{lat} = 0.5\%$

$\Rightarrow$ still gives best accuracy for $|V_{us}|$

- $\delta(f_+(0) - 1)^{\text{lat}} \simeq 15\%$ will be reduced
  $\longrightarrow$ by use of partially twisted boundary conditions (Bedaque '04, Sachrajda et al '05) applied to form factors in (Guadagnoli et al '06, RBC/UKQCD '07-08, ETM '07)
  $\Rightarrow f_+(q^2)$ directly at $q^2 = 0$ (UKQCD '07)
  $\longrightarrow$ simulations closer to physical QCD point

- important to have $a \to 0$
  $\longrightarrow$ partially done for $N_f = 2$ (ETM '09)

$|V_{us}|$ from $K \to \mu\bar{\nu}$

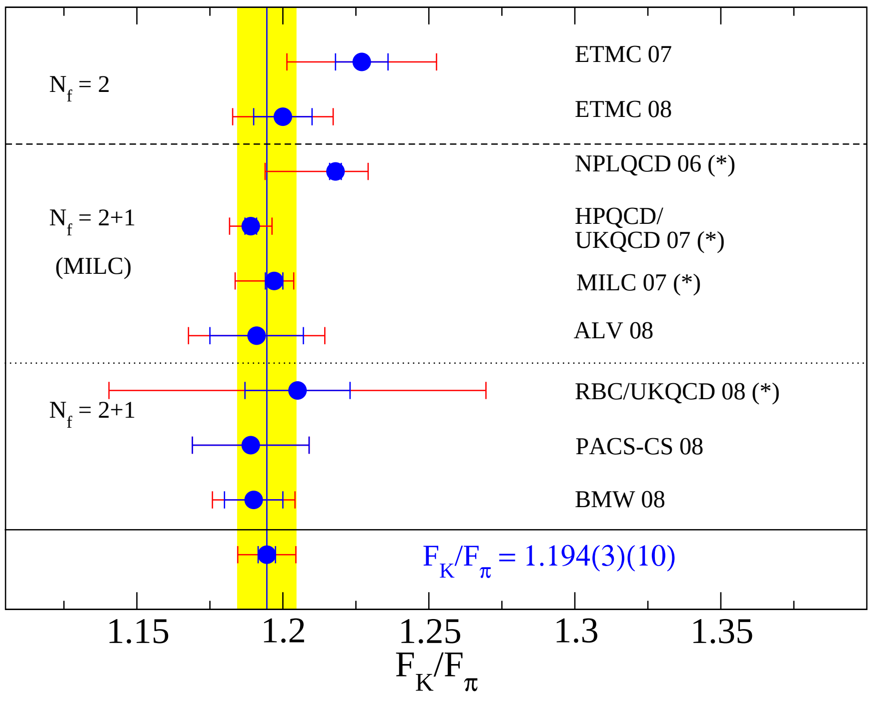
Marciano '04: window of opportunity (PDG '08)

$$\frac{\Gamma(K \to \mu\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} \longrightarrow \frac{|V_{us}|}{|V_{ud}|}\frac{F_K}{F_\pi} = 0.2757(7)\ [0.25\%]$$

Need nonperturbative QCD calculation of $F_K/F_\pi - 1 = O\left(\frac{m_s - m_{ud}}{\Lambda}\right) \sim 0.2$ to:

- 2.5% to match $\delta|V_{ud}|$ contribution to unitarity sum
- 1.6% to match experimental error in $K \to \mu\bar{\nu}(\gamma)/\pi \to \mu\bar{\nu}(\gamma)$

F_K/F_π from the lattice: unquenched summary



- $\delta(F_K/F_\pi)^{lat} = 0.8\% \Leftrightarrow$ $\delta(F_K/F_\pi - 1)^{lat} \simeq 5\%$

$\Rightarrow$ relative accuracy on calculated $SU(3)$ breaking effect much better than for $f_+^{K^0\pi^-}(0)$

$\Rightarrow$ still leads to larger theory error on $|V_{us}|$ (0.8% vs 0.5%)

- F_K/F_π straightforward to calculate

$\Rightarrow$ should be able to reach the $\delta(F_K/F_\pi - 1)^{lat} \sim 1.6\%$ required for $\delta^{th}|V_{us}| \sim 0.25\%$, i.e. today's experimental accuracy, in near future

$|V_{us}|$ from experiment and the lattice

- $(K_{\ell 2}/\pi_{\ell 2})$ and lattice
  $\longrightarrow |V_{us}/V_{ud}| = 0.2309(6)_{exp}(6)_{stat}(19)_{syst} = 0.2309(21)$ [0.9%]
- $K_{\ell 3}$ and lattice
  $\longrightarrow |V_{us}| = 0.2247(5)_{exp}(7)_{stat}(9)_{syst} = 0.2247(13)$ [0.6%]
- $|V_{ub}|^2 \simeq 1.5 \cdot 10^{-5}$

Using only lattice input, find

$$\frac{G_q^2}{G_\mu^2}|V_{us}|^2\left[1+|V_{ud}/V_{us}|^2\right] = 0.998(21) \quad [2\%]$$

Using all input (Flavianet '08), get (LL '09)

$$\frac{G_q^2}{G_\mu^2}\left[|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2\right] = 0.9999(6) \quad [0.06\%]$$

$\Rightarrow$ cannot exclude NP w/ scale $\Lambda_{NP} \gtrsim 3 \div 2\,\mathrm{TeV}$ @ $1 \div 3\sigma$

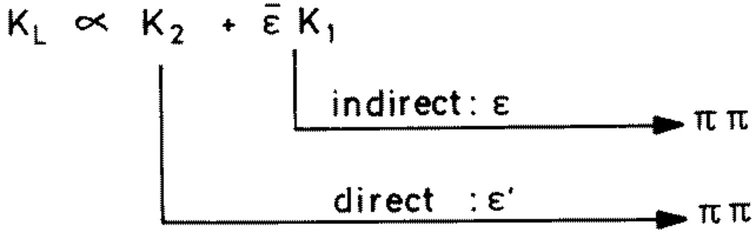
$K \longrightarrow \pi\pi$ decays: phenomenology

$$-iT[K^0 \to \pi^+\pi^-] = \sqrt{\tfrac{1}{3}}A_0 e^{i\delta_0} + \sqrt{\tfrac{1}{6}}A_2 e^{i\delta_2} \qquad -iT[K^+ \to \pi^+\pi^0] = \tfrac{\sqrt{3}}{2}A_2 e^{i\delta_2}$$

$$-iT[K^0 \to \pi^0\pi^0] = -\sqrt{\tfrac{1}{3}}A_0 e^{i\delta_0} + \sqrt{\tfrac{2}{3}}A_2 e^{i\delta_2}$$

CP violation implies $A_I^* \neq A_I$

$$\Delta M_K = M_{K_L} - M_{K_S} \simeq 2\,\mathrm{Re}M_{12}$$



$$\epsilon \equiv \frac{T[K_L \to (\pi\pi)_{I=0}]}{T[K_S \to (\pi\pi)_{I=0}]} \simeq \frac{1}{\sqrt{2}} e^{i\pi/4} \frac{\mathrm{Im}M_{12}}{\Delta M_K}$$

$$\epsilon' \simeq \frac{1}{\sqrt{2}} e^{i\pi/4}\,\mathrm{Im}\left(\frac{A_2}{A_0}\right)$$

Experimentally:

(PDG '06)

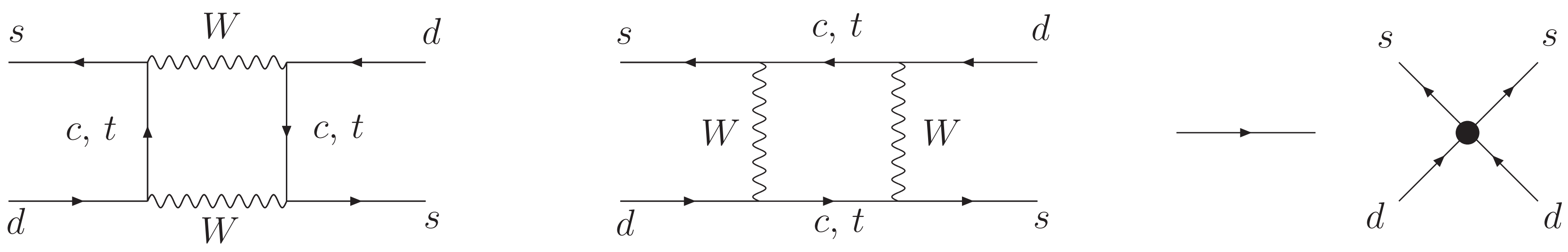
$$\Delta M_K = (3.483 \pm 0.006) \times 10^{-12}\,\mathrm{MeV} \quad [0.2\%]$$

$$|A_0/A_2| \simeq 22.2 \qquad (\Delta I = 1/2 \text{ rule})$$

$$|\epsilon| = (2.229 \pm 0.012)\cdot 10^{-3} \quad [0.5\%]$$

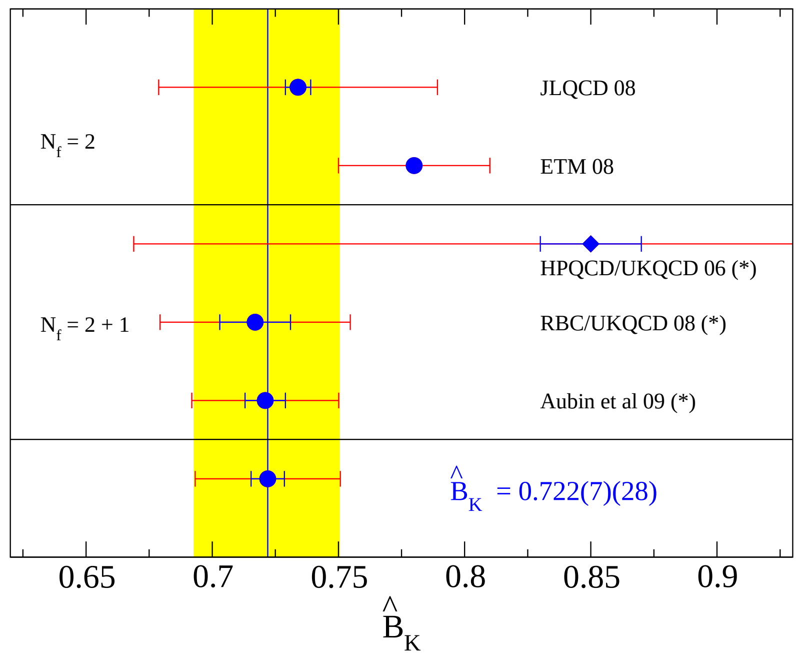
$$\mathrm{Re}(\epsilon'/\epsilon) = (1.65 \pm 0.26)\cdot 10^{-3} \quad [16\%]$$

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



$$2M_K M_{12}^* = \langle \bar{K}^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | K^0 \rangle = C_1^{\text{SM}} \hat{Z}_1(\mu) \langle \bar{K}^0 | O_1(\mu) | K^0 \rangle$$

$$O_1 = (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} \qquad \langle \bar{K}^0 | O_1(\mu) | K^0 \rangle = \frac{16}{3} M_K^2 F_K^2 B_K(\mu)$$



- Unquenched summary of $\hat{B}_K \equiv \hat{Z}_1(\mu) B_K(\mu)$
- Aubin et al '09 perform first $N_f \geq 2$ study of a-dependence
  $\longrightarrow$ important to check with larger a range
- $B_K^{N_f=2+1} / B_K|_{JLQCD}^{N_f=0} = 0.84(7)$ (JLQCD '97, staggered)
  $\longleftarrow$ not only quenching (LL '09)
  $\longrightarrow$ problem w/ staggered? 1-loop matching?
- $\delta B_K^{lat} = 4\%$
  $\longrightarrow$ is this good enough?

$K^0 - \bar{K}^0$ mixing in the SM: phenomenology

Actually (Buchalla et al '96, Anikeev et al '02, Buras & Guadagnoli '08)

$$\epsilon \simeq e^{i\phi_\epsilon} \sin\phi_\epsilon \left[\frac{\mathrm{Im}M_{12}}{\Delta M_K} + \xi\right]$$

with $\phi_\epsilon = 43.5(7)^o$[1.6%] (PDG '08), not 45^o, and $\xi \equiv \mathrm{Im}A_0/\,\mathrm{Re}A_0 \simeq -0.06(2)\sqrt{2}|\epsilon|$, not zero

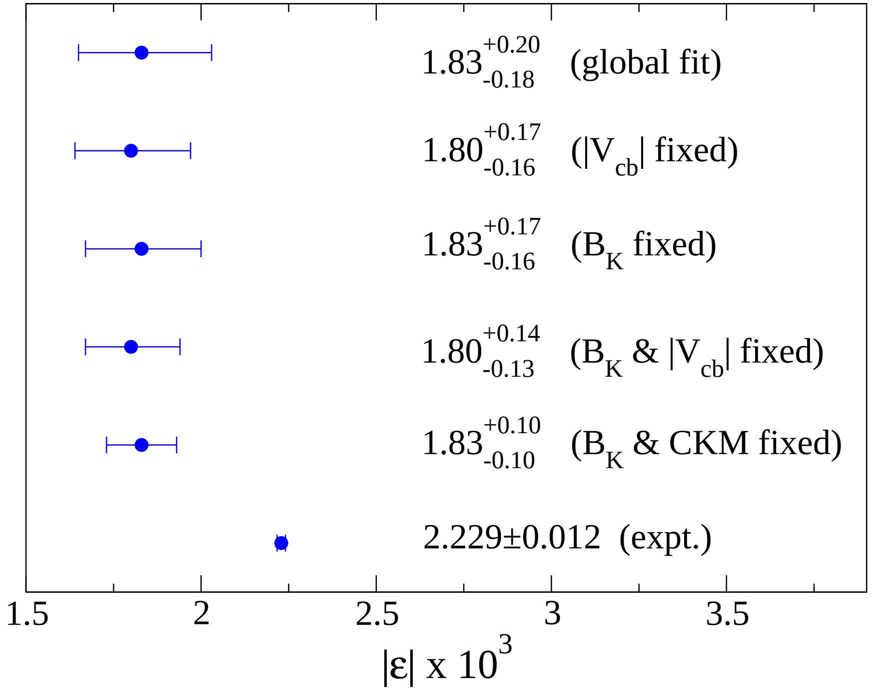
$$\Rightarrow |\epsilon| \simeq \kappa_\epsilon C_\epsilon \hat{B}_K \lambda^2 \bar{\eta}^2 |V_{cb}|^2 \left[|V_{cb}|^2(1-\bar{\rho})\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c\right]$$

- $\longrightarrow$ expect significant contribution of $\delta|V_{ub}|$ to $\delta|\epsilon|$
- $\longrightarrow$ with $\kappa_\epsilon \simeq \sqrt{2}\sin\phi_\epsilon(1+\xi/(\sqrt{2}|\epsilon|)) = 0.92(2)$ and lower $\hat{B}_K$, expect smaller SM prediction for $|\epsilon|$

ϵ from global CKM fit: tension with the SM?

CKM fits w/ $\hat{B}_K = 0.723(11)(35)$ [5%] and $|V_{cb}| = 0.04059(38)(58)$ [1.7%] give

(Thanks to J. Charles (CKMfitter 09 input))



- Non-B_K error in $|\epsilon| \sim 9\%$
- Roughly same for non-$|V_{cb}|$ error
- Error on κ_ϵ and perturbative contributions account for $\sim 1/2$ total 10% error on $|\epsilon|$

$\Rightarrow$ improve B_K further if $\delta|V_{cb}|$ at least, and eventually contributions from other CKM and even perturbative parameters and κ_ϵ are also improved

Above shows potential tension betweem SM and experiment: (Lunghi et al '08, Buras et al '08)

- $2\,\sigma$ effect
- becomes $3\,\sigma$ for $\delta B_K = \delta|V_{cb}| = 0 \ldots$
- $\ldots$ and $4\,\sigma$ for $\delta B_K = \delta V_{\mathrm{CKM}} = 0$

Tension between ϵ and $\sin 2\beta_{\psi K_S}$

Keeping only tt contribution and assuming no NP in CP conserving part of $B_{d(s)}-\bar{B}_{d(s)}$ (Buras et al '08)

$$|\epsilon| \sim \kappa_\epsilon F_K^2 \hat{B}_K |V_{cb}|^4 \left[f_{B_s}^2 B_{B_s}/f_{B_d}^2 B_{B_d}\right] \sin 2\beta$$

$\Rightarrow$ NP in $\Delta F = 2$ observables (Lunghi et al '08, Buras et al '08-'09)

$\rightarrow$ perfect intro for discussing heavy-quark physics from LQCD in second $1/2$ of my talk!?!

Conclusion

- Lattice QCD simulations have made tremendous progress in the last few years
- It is now possible to perform $2+1$ flavor lattice calculations that allow to reach the physical (isospin symmetric) QCD point ($M_\pi \simeq 135\,\mathrm{MeV}$, $M_K = 495\,\mathrm{MeV}$, $a \to 0$, $L \to \infty$) in a controlled fashion
- Some simulations are now being performed very very near $M_\pi \simeq 135\,\mathrm{MeV}$ (PACS-CS '08-'09)
- Impact on phenomenology is huge: typical error down from 15% ($N_f = 0$ or $N_f = 2$ w/ $M_\pi \gtrsim 500\,\mathrm{MeV}$) to a few %
- The light hadron spectrum, obtained w/ a $2+1$ flavor calculation in which extrapolations to the physical point are under control, agrees w/ measured spectrum at level of a few %
- Many more quantities are being computed: individual decay constants, quark masses, other strange, charm and bottom weak matrix elements, including of BSM operators, etc.

  $\longrightarrow$ highly relevant for *flavor physics*
- It is still hard work, but the age of precision nonperturbative QCD calculations is finally dawning