Heavy quarks on the lattice: future perspectives

Rainer Sommer

DESY, A Research Centre of the Helmholtz Association

SFB meeting, Zeuthen, March 2009

The principle

First principle "solution" of QCD

experiments, hadrons

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M_\pi &= 139.570\,\mathrm{MeV} \\
m_\mathrm{K} &= 493.7\,\mathrm{MeV} \\
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fundamental parameters & hadronic matrix elements

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m_\mathrm{c}(\mu)\,,\ m_\mathrm{b}(\mu) \\
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- **Non-perturbative regulator: lattice with spacing** a

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continuum limit $a \longrightarrow 0$

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Some sample results from the literature

Review of E. Gamiz lattice 2008

examples of results

$m_{\mathrm{c}}^{\overline{\mathrm{MS}}}(3\,\mathrm{GeV})$	$=$	$0.986(10)\,\mathrm{GeV}$	HPQCD
$m_{\mathrm{b}}^{\overline{\mathrm{MS}}}(m_{\mathrm{b}})$	$=$	$4.20(4)\,\mathrm{GeV}$	HPQCD
$\xi = \frac{F_{\mathrm{B_s}}\sqrt{m_{\mathrm{B_s}}}}{F_{\mathrm{B}}\sqrt{m_{\mathrm{B}}}}$	$=$	$1.211(38)(24)$	FNAL/MILC
$F_{\mathrm{B_s}}$	$=$	$243(11)\,\mathrm{MeV}$	FNAL/MILC
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Precision up to 1 % is claimed

The machinery 

The present numbers quoted for phenomenology with small errors are dominated by "rooted staggered" sea quark computations [MILC-collaboration]

rooting: (sea quarks)

- $\longrightarrow$ non-local
- locality (= renormalizability = correctness) argued to be recovered as $a \longrightarrow 0$ [Bernard,Golterman,Sharpe]
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NRQCD (or Fermilab action) for b-quarks

- power law divergences
  ($a \propto \mathrm{e}^{-1/2b_0\, g_0^2}$)

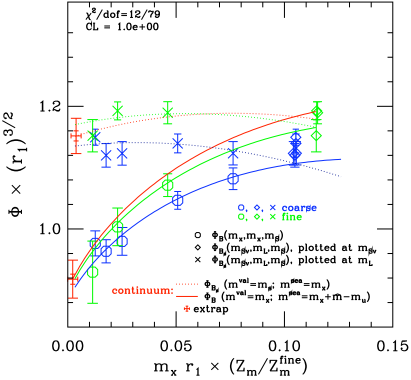
$$\frac{g_0^{2k}}{a\ m_b} \sim \frac{1}{a\,[\log(a)]^k\, m_\mathrm{b}} \xrightarrow{a\to 0} \infty$$

delicate analysis of continuum limit

The machinery

staggered chiral perturbation theory

$m \to (m_{\mathrm{u}} + m_{\mathrm{d}})/2$ & $a \to 0$ in one (necessary due to rooting)

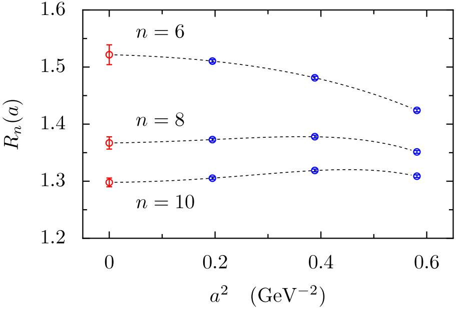


many parameter fits

The machinery

Baysian fits

$a \longrightarrow 0$ from high order polynomial in a with few points



The machinery

It appears good to perform independent computations with an independent technology

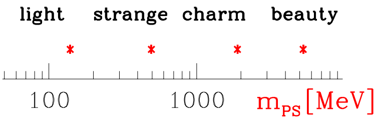
- manifestly local
- non-perturbative subtraction of power law divergences

Such computations are in progress

... but first let us understand that LQCD is a challenge

The challenge

multiple scale problem
always difficult
for a numerical treatment



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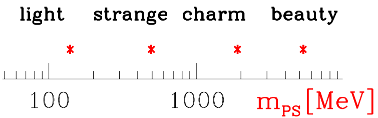

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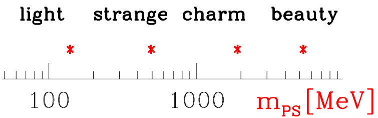

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$$\mathrm{O}(\mathrm{e}^{-LM_\pi}) \qquad\qquad m_{\mathrm{D}}\,a \lesssim 1/2$$

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$$L \gtrsim 4/M_\pi \sim 6\,\mathrm{fm} \qquad\qquad a \approx 0.05\,\mathrm{fm}$$

$$L/a \gtrsim 120$$

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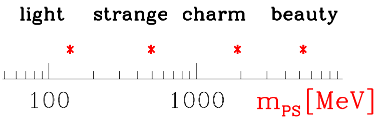

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beauty not yet accomodated: effective theory, $\Lambda_{\rm QCD}/m_{\rm b}$ expansion

Perspectives

First let me state, there is ChPT so $m_\pi = 280\,\mathrm{MeV}$ and a theory-guided extrapolation seems good enough
$\rightarrow\ L \approx 3\,\mathrm{fm}\,,\ L/a = 64$

In addition there is ChPT including $\mathrm{O}(a^2)$-effects
[Singleton & Sharpe; O. Bär, G.Rupak & N.Shoresh]

and

- new algorithms
- new machines
- development / demonstration of **effective field theory strategies**

Perspectives: algorithms for dynamical fermions

- mass preconditioning [M. Hasenbusch]
- multiple time scale integrators [Sexton & Weingarten; C. Urbach et al.]
- odd number of flavours, $m_\mathrm{s} \neq m_\mathrm{c}$:
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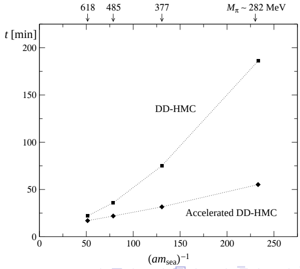

Perspectives: machines

For illustration: the German situation (roughly)

year	machine	speed/Tflops	share for a typical collaboration
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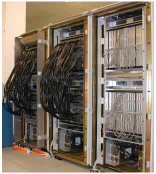

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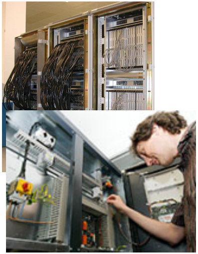

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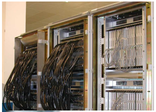
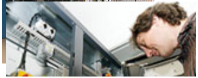
2009.5	BG/P	1000.0000	/20(?)





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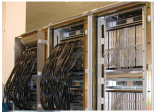
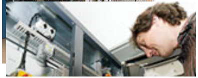



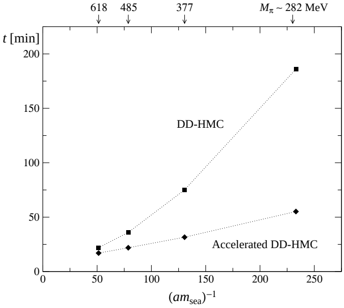

Growth (recently) stronger than Moore's law

Perspectives: algorithms & machines

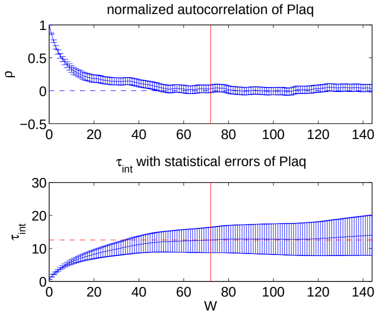
Example: 128×64^3, $a = 0.04\,\mathrm{fm}$, $L = 2.6\,\mathrm{fm}$

at $m_q = m_\mathrm{s}/2$: (2 trajectories)/hour=(1 MD unit)/hour

on 1024 node BG/P (1/64 Pflops)



execution time of accelerated DD-HMC



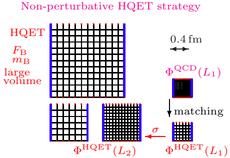
$2\tau_{int} = \#$ MD unit per effective independent measurement

256×128^3 at the physical point ($M_\pi = M_\pi^{\mathrm{physical}}$) seems in reach

Perspectives: strategies for *b* quark

- Non-perturbative HQET (expansion in $\Lambda_{\rm QCD}/m_{\rm b}$)
  [Heitger& S., 2001]
- Step scaling strategy
  [G.M. de Divitiis, M. Guagnelli, F. Palombi, R. Petronzio & N. Tantalo]

Very much related and may be combined!

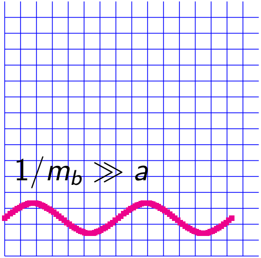


Non-perturbative matching of HQET and QCD

- The trick: start in small volume, $L = L_1 \approx 0.4\,\mathrm{fm}\,, \quad a = 0.01\,\mathrm{fm}$

Φ_k finite volume masses, decay constants ...

QCD

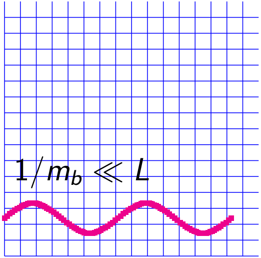


$$\Phi_k^{\mathrm{QCD}} = \Phi_k^{\mathrm{HQET}}$$

$k = 1, 2, \ldots, N_{\mathrm{HQET}}$

$N_{\mathrm{HQET}} =$
# of parameters

HQET



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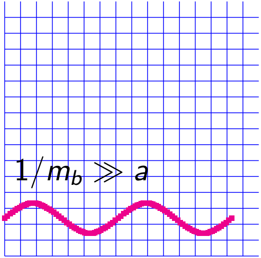

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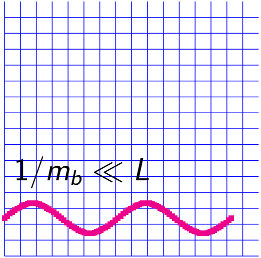


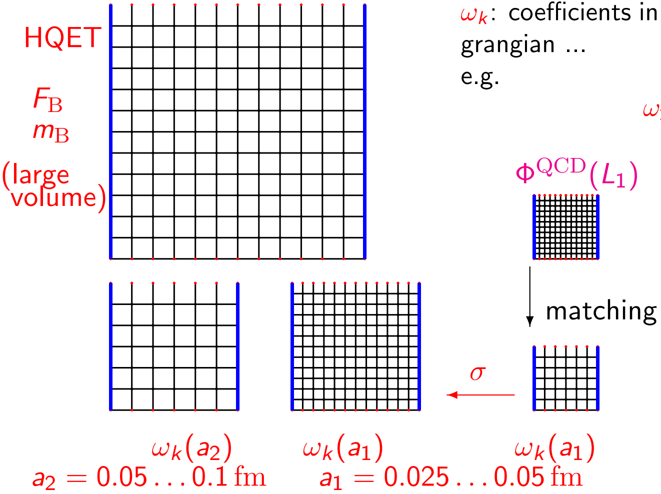
$\rightarrow$ HQET-parameters from QCD-observables in small volume

– at small lattice spacing $\quad L^{-1} \ll m_{\mathrm{b}} \ll a^{-1}$

power divergences subtracted non-perturbatively

The HQET strategy: first view

ω_k: coefficients in effective Lagrangian ...
e.g. $\omega_2\, \bar{b}\, \sigma \cdot \mathbf{B}\, b$
$\omega_2 \sim 1/(2m_\mathrm{b})$



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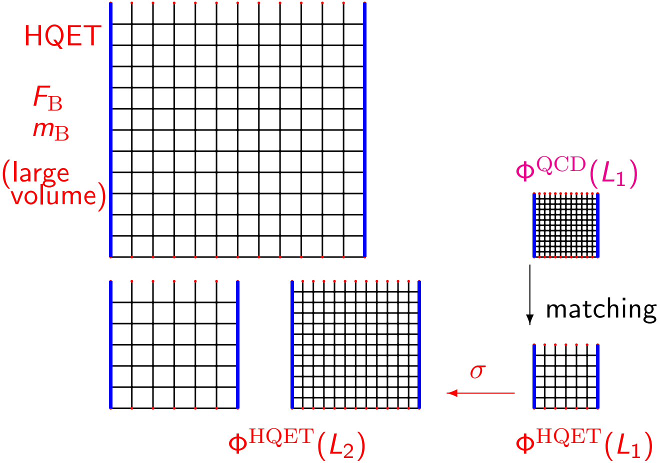

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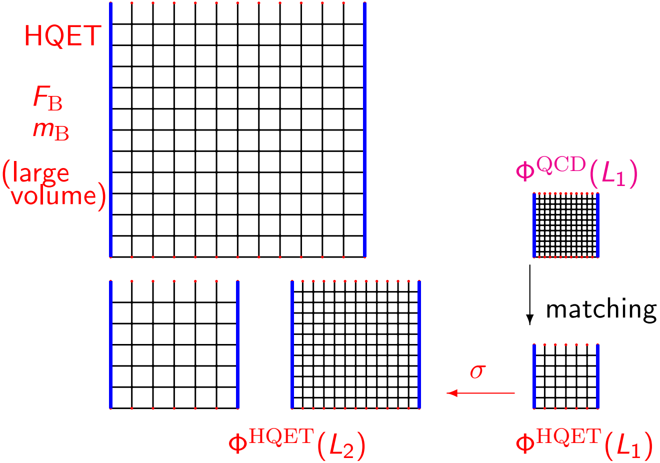

- continuum limit can be taken in all steps

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In $F_{\rm B}$: $\mathrm{O}(\Lambda^2/m_{\rm b}^2) = 2(1)\%$ [Blossier, Della Morte, Garron & S]

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- $\overline{m}_{\rm b}^{\overline{\rm MS}}(\overline{m}_{\rm b}) = 4.347(48)\mathrm{GeV}$ quenched, $r_0 = 0.5\,\mathrm{fm}$ (4-loop RGE)
[Della Morte, Garron, Papinutto & S]

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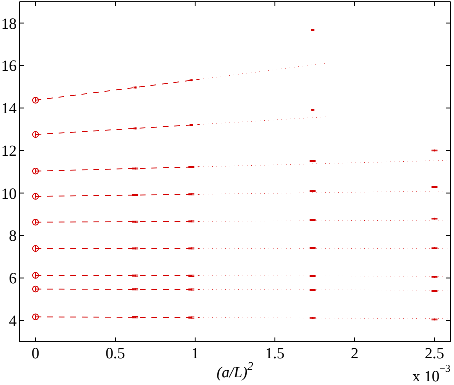
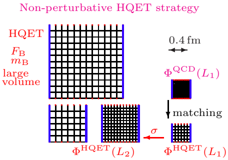
In $F_{\rm B}$: $\mathrm{O}(\Lambda^2/m_{\rm b}^2) = 2(1)\%$ [Blossier, Della Morte, Garron & S]

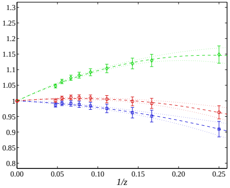
- $\Lambda^3/m_{\rm b}^3$ corrections expected to be negligible
- $\overline{m}_{\rm b}^{\overline{\rm MS}}(\overline{m}_{\rm b}) = 4.347(48)\mathrm{GeV}$ quenched, $r_0 = 0.5\,\mathrm{fm}$ (4-loop RGE)
  [Della Morte, Garron, Papinutto & S]
- And with previous strategy (static with $x \propto 1/m_{\rm b}$ interpolations)
  $\overline{m}_{\rm b}^{\overline{\rm MS}}(\overline{m}_{\rm b}) = 4.421(67)\mathrm{GeV}$ [Guazzini, S., Tantalo]
- 1–1.5% precision; uncertainty dominated by $\Delta Z_{\rm M}$, $M = Z_{\rm M}\, m_0$

Perspectives: dynamical fermions are absolutely needed

At present this strategy is being applied to $N_\mathrm{f} = 2$ QCD
(just up and down sea)





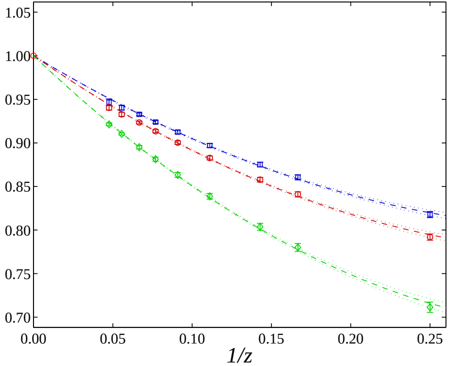


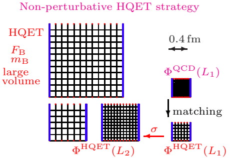
in progress within CLS $\Uparrow 1/z = 1/(M_b\, L)$.

B. Blossier, G. De Divitiis, M. Della Morte, P. Fritzsch, N. Garron, J. Heitger, G. von Hippel, T. Mendes, R. Petronzio, S. Schäfer, H. Simma, R.S., N. Tantalo

Dynamical fermions continued

At present this strategy is being applied to $N_{\mathrm{f}} = 2$ QCD
(just up and down sea)
Verification of approach to the spin-symmetric limit

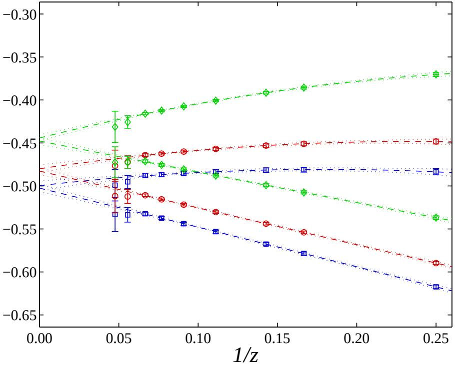




Ratio of axial-vector and vector correl. fct. No.1

At present this strategy is being applied to $N_\mathrm{f} = 2$ QCD (just up and down sea)

Verification of approach to the spin-symmetric limit



Ratio of axial-vector and vector correl. fct. No.2

Dynamical fermions continued

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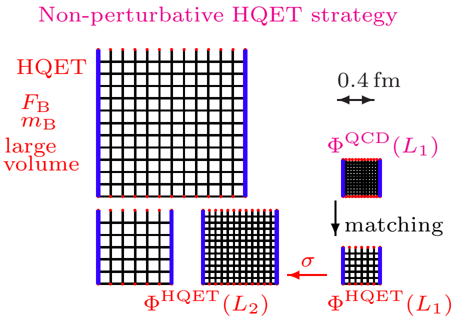


Step scaling functions in progress, large volume, see next talk.

$N_{\mathrm{f}} = 2$ QCD: Coordinated Lattice Simulations

Teams

* Berlin (team leader Ulli Wolff)
* CERN (L. Giusti, M. Lüscher)
* DESY-Zeuthen (Rainer Sommer)
* Madrid (Carlos Pena)
* Mainz(Hartmut Wittig)
* Rome (Roberto Petronzio)
* Valencia (Pilar Hernández)

Physics planned at present

* Fundamental parameters up to M_{b}
* Pion interactions
* Baryon physics
* Kaon physics

also with mixed actions

β	a[fm]	lattice	L[fm]	masses	
5.30	0.08	48×24^3	1.9	6 masses	CERN, Rome
5.30	0.08	64×32^3	2.6	6 masses	CERN, Rome
5.50	0.06	64×32^3	1.9	5 masses	DESY,Berlin,Madrid
5.70	0.04	96×48^3	1.9	2 masses	DESY,Berlin
5.70	0.04	128×64^3	2.6	2 masses	DESY,Berlin, started

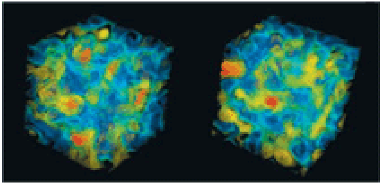
Promising for charm and beauty

Conclusions: the present mood

BREAKTHROUGHS OF THE YEAR

9) Proton's Mass 'Predicted' [Dürr et al.]

Thanks to the uncertainties of quantum mechanics, however, myriad gluons and quark-antiquark pairs flit into and out of existence within a proton in a frenzy that's nearly impossible to analyze but that produces 95% of the particle's mass.



Conclusions: the present mood

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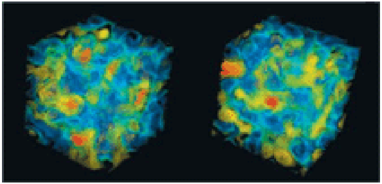

$E = mc^2$ "belegen die Forscher Einsteins Spezielle Relativitätstheorie von 1905 auf subatomarer Ebene: "Auch dort sind Energie und Masse äquivalent. Aber das war bisher nur eine Hypothese", sagte Lellouch."

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Conclusions: the present mood

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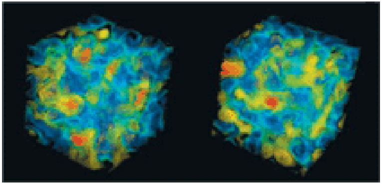

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this is going a bit overbord but there are **good perspectives** for matching experimental **precisions** on

(semi-) leptonic B decays, B-mixing; not on purely hadronic decays!

...

by the time superB comes