Recent lattice results on QCD thermodynamics

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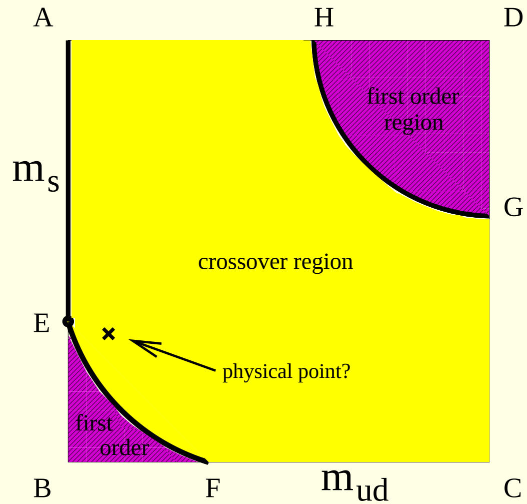
1. Introduction
2. The nature of the transition: broad cross-over
3. The transition temperature: T_c
4. The equation of state at large temperatures
5. Discrepancy with RBC-Bielefeld/hotQCD
6. Conclusions

Standard picture of the phase diagram and its uncertainties



physical quark masses: important for the nature of the transition

n_f=2+1 theory with m_q=0 or ∞ gives a first order transition

for intermediate quark masses we have an analytic cross over (no χPT)

F.Karsch et al., Nucl.Phys.Proc. 129 ('04) 614; G.Endrodi et al. PoS Lat'07 182('07);

de Forcrand, S. Kim, O. Philipsen, Lat'07 178('07)

continuum limit is important for the order of the transition:

n_f=3 case (standard action, N_t=4): critical $m_{ps}\approx$300 MeV

with different discretization error (p4 action, N_t=4): critical $m_{ps}\approx$70 MeV

the physical pseudoscalar mass is just between these two values

discretization errors change the order of the transition

what happens for physical quark masses, in the continuum, at what T_c?

Partition function

$$Z = \int dU d\Psi d\overline{\Psi} e^{-S_E}$$

S_E is the Euclidean action

Parameters:

- gauge coupling g
- quark masses m_i ($i = 1..N_f$)
- (Chemical potentials μ_i)
- Volume (V) and temperature (T)

Finite $T \leftrightarrow$ finite temporal lattice extension

$$T = \frac{1}{N_t a}$$

Continuum limit: $a \rightarrow 0$

Renormalization: keep the physical spectrum constant

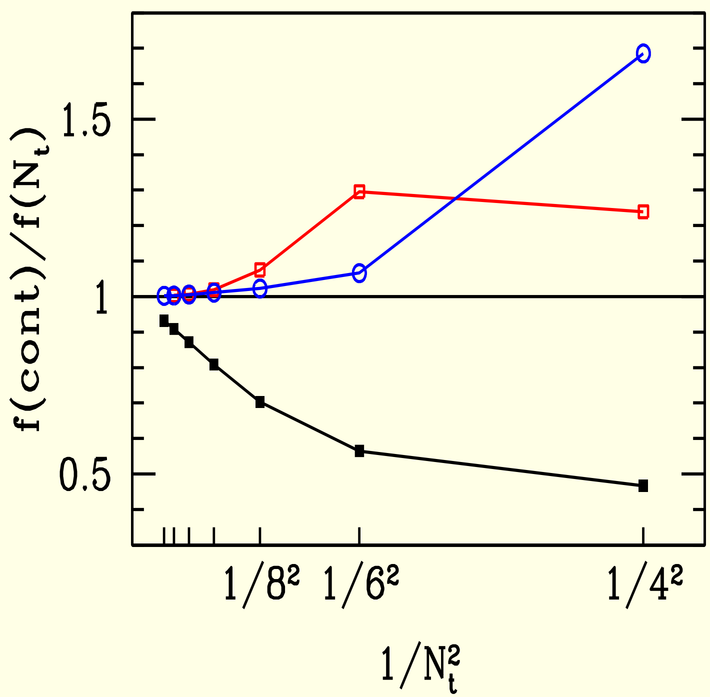
at finite T:

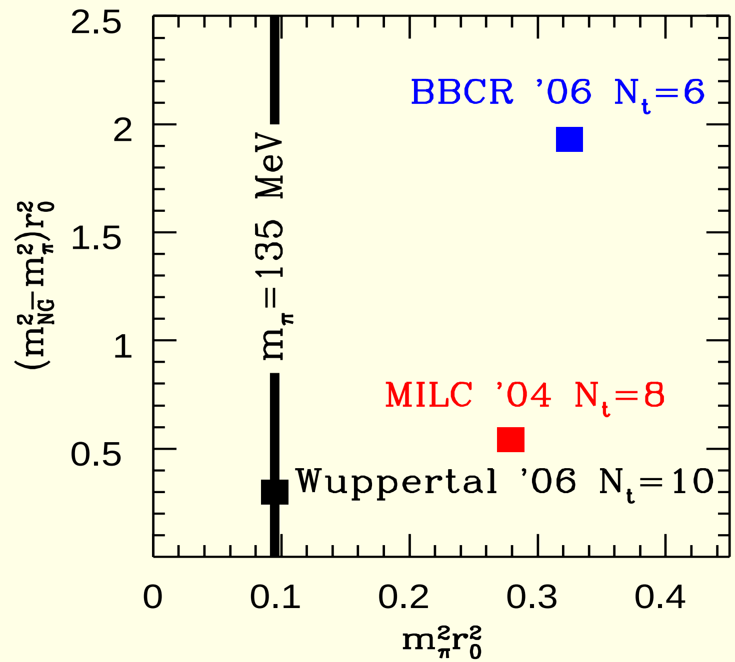
continuum limit $\Longleftrightarrow N_t \rightarrow \infty$

The nature of the QCD transition

Y.Aoki, G.Endrodi, Z.Fodor, S.D.Katz, K.K.Szabo, Nature, 443 (2006) 675 [hep-lat/0611014]

Symanzik improved gauge, stout improved n_f=2+1 staggered fermions
simulations along the line of constant physics: m_π=135 MeV, m_K=500 MeV

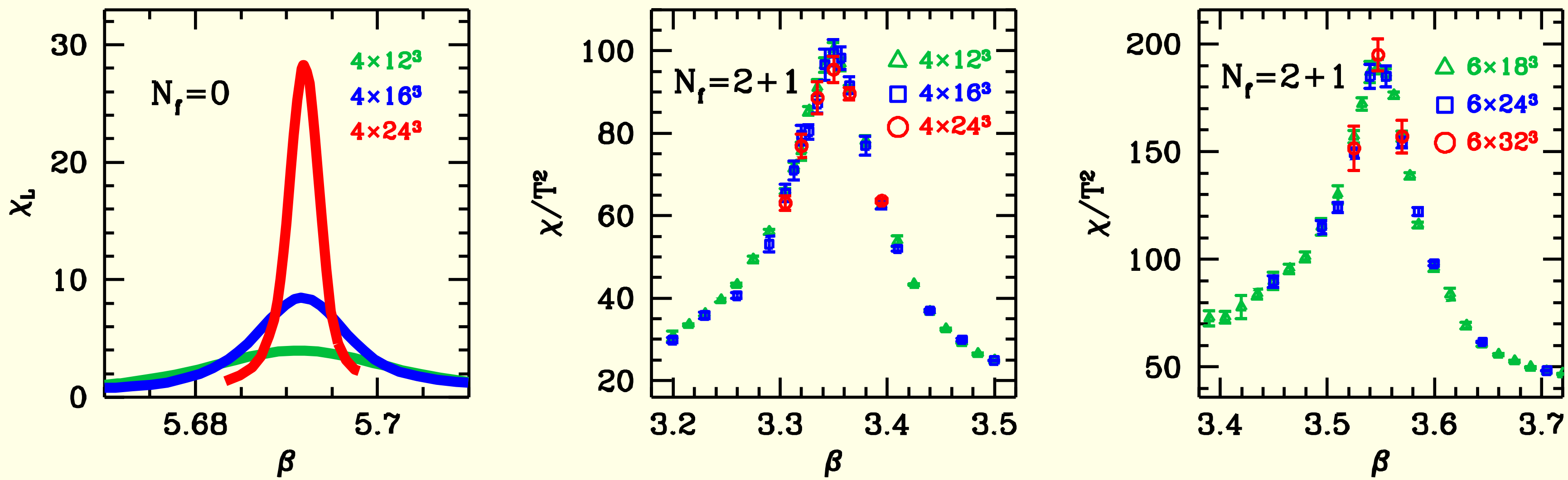




extrapolation from N_t and N_t+2 (standard action) ≈ as good as N_t with p4
N_t=8,10 gives ≈ ±1%, but a<0.15, 0.12 fm needed to set the scale (±1%)
thermodynamic quantities are obtained "more precisely" than the scale
(p4 independent config. is >10× more CPU ⇒ instead balance: a→0)

• finite size scaling for the chiral susceptibility: χ=(T/V)∂^2logZ/∂m^2

first order transition $\Longrightarrow$ peak width $\propto$ 1/V, peak height $\propto$ V
cross-over $\Longrightarrow$ peak width $\approx$ constant, peak height $\approx$ constant



eight times larger volumes: volume independent scaling $\Rightarrow$ cross-over

do we get the same result (cross-over) in the continuum limit?
one might have the unlucky case as we had in n_f=3 QCD:
discretization errors changed the nature of the transition for physical m_{ps}

• How to get rid of the discretization errors?

a. susceptibility for fixed physical volumes in the continuum
b. finite size analysis of the continuum extrapolated values

renormalize the susceptibility the same way as the free energy

$$f(T) \propto \log Z(T\neq 0)/V_4 - \log Z(T=0)/\bar{V}_4$$

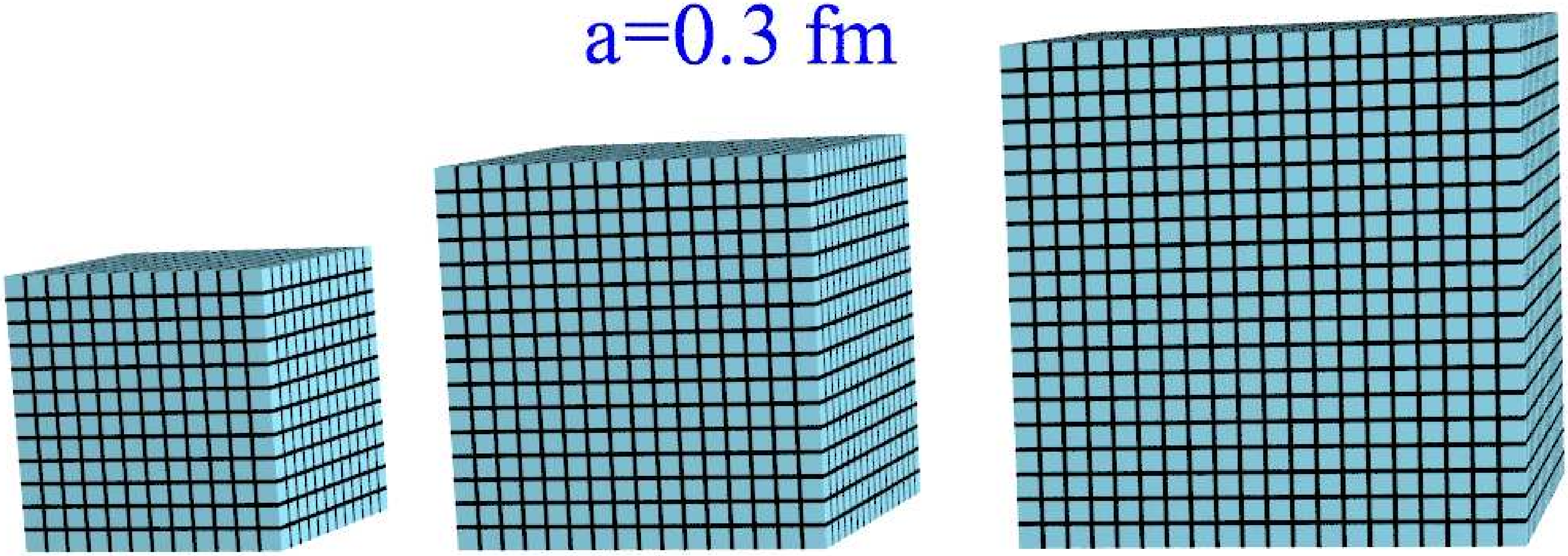
$p(T)$ has a continuum limit and we can use $m_r = Z_m \cdot m$

$$\chi_r(T) = \partial^2/(\partial m_r^2)\,[\log Z(T\neq 0)/V_4 - \log Z(T=0)/\bar{V}_4]$$

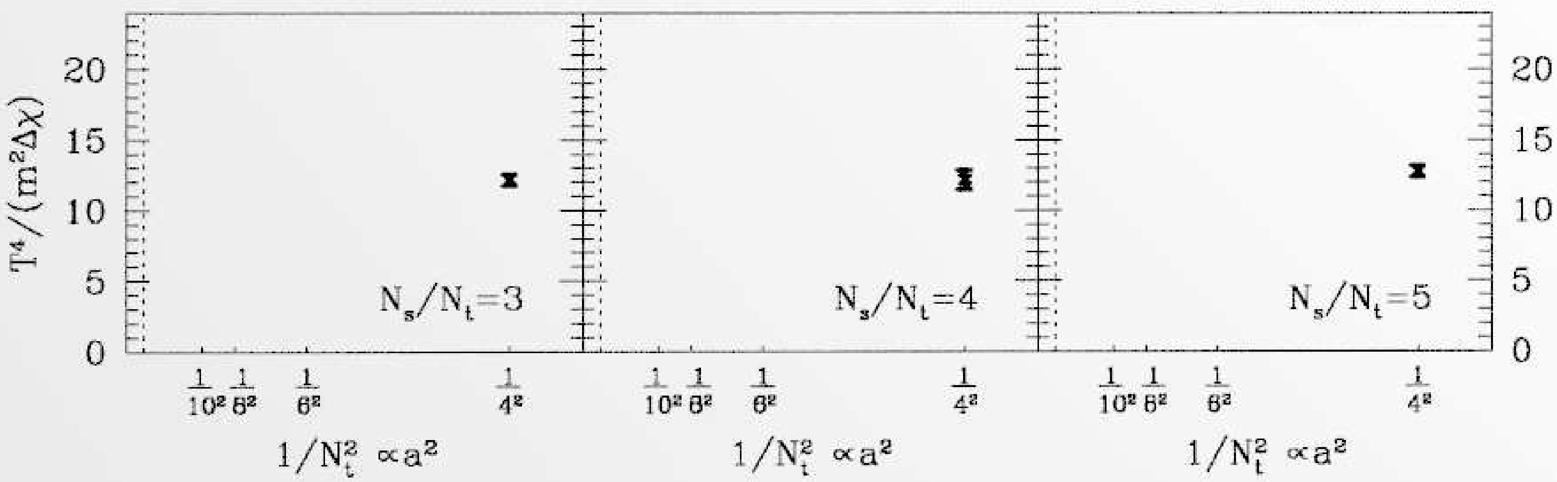
construct a quantity in continuum: Z_m drops out from $m^2\partial^2/\partial m^2$

$$\Longrightarrow m_r^2 \cdot \chi_r(T) = m^2 \cdot [\chi(T\neq 0) - \chi(T=0)]$$

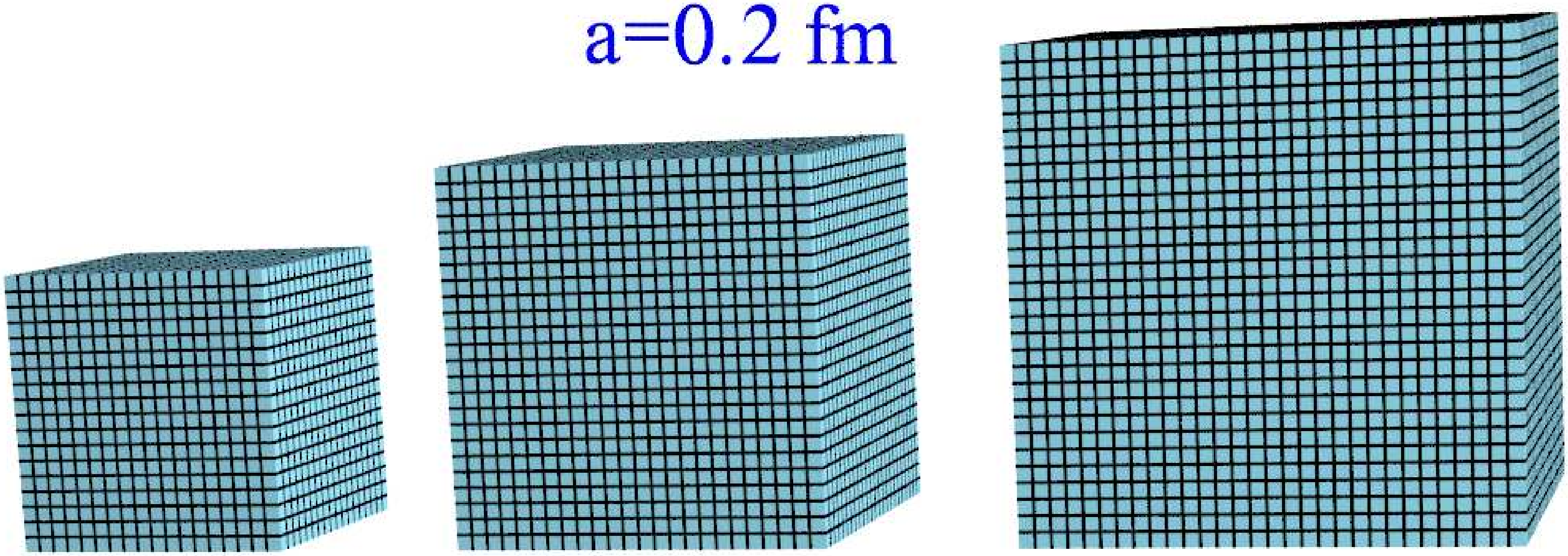
a=0.3 fm



3.6 fm 4.8 fm 6 fm



a=0.2 fm



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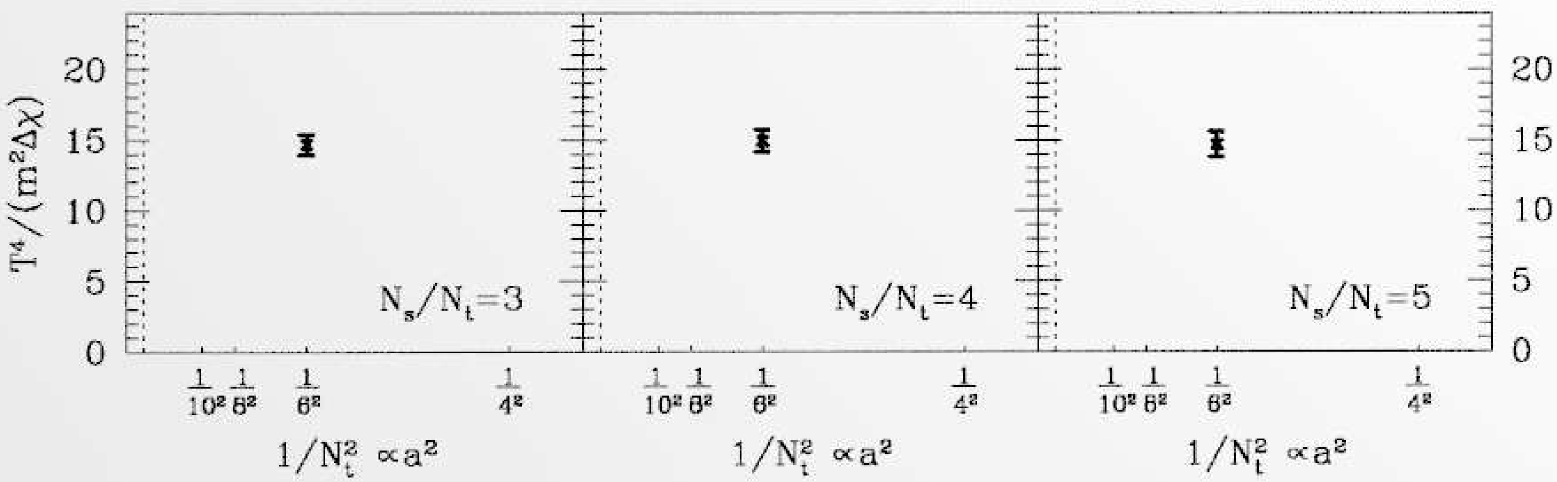
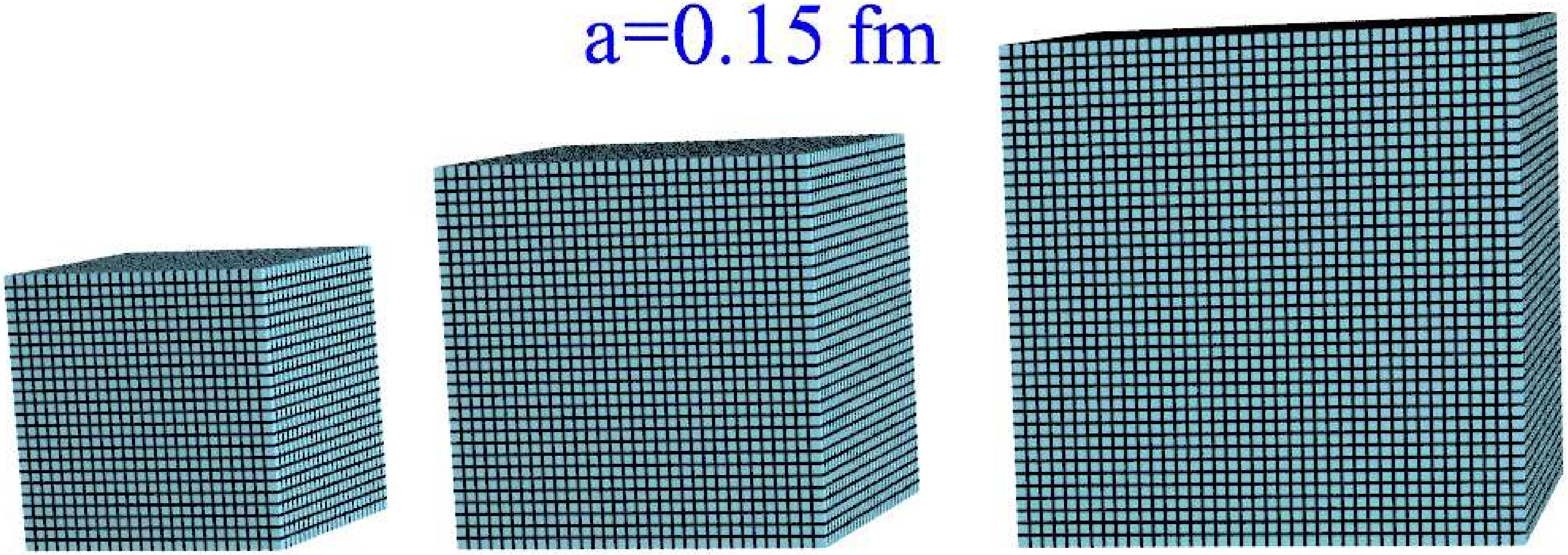


a=0.15 fm



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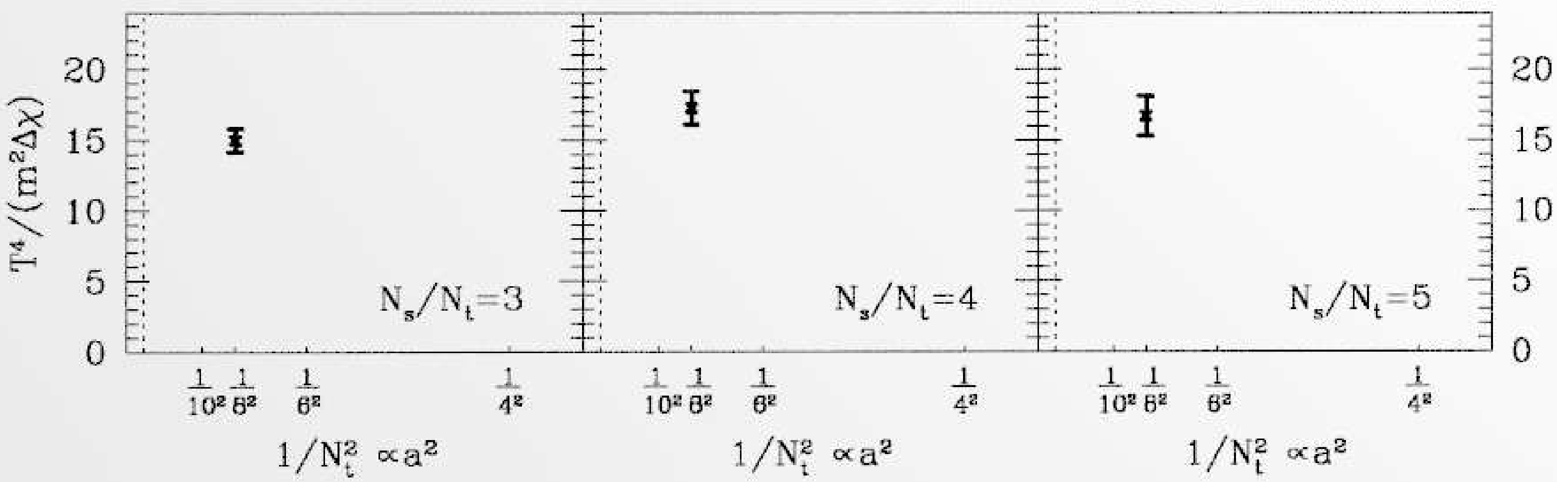
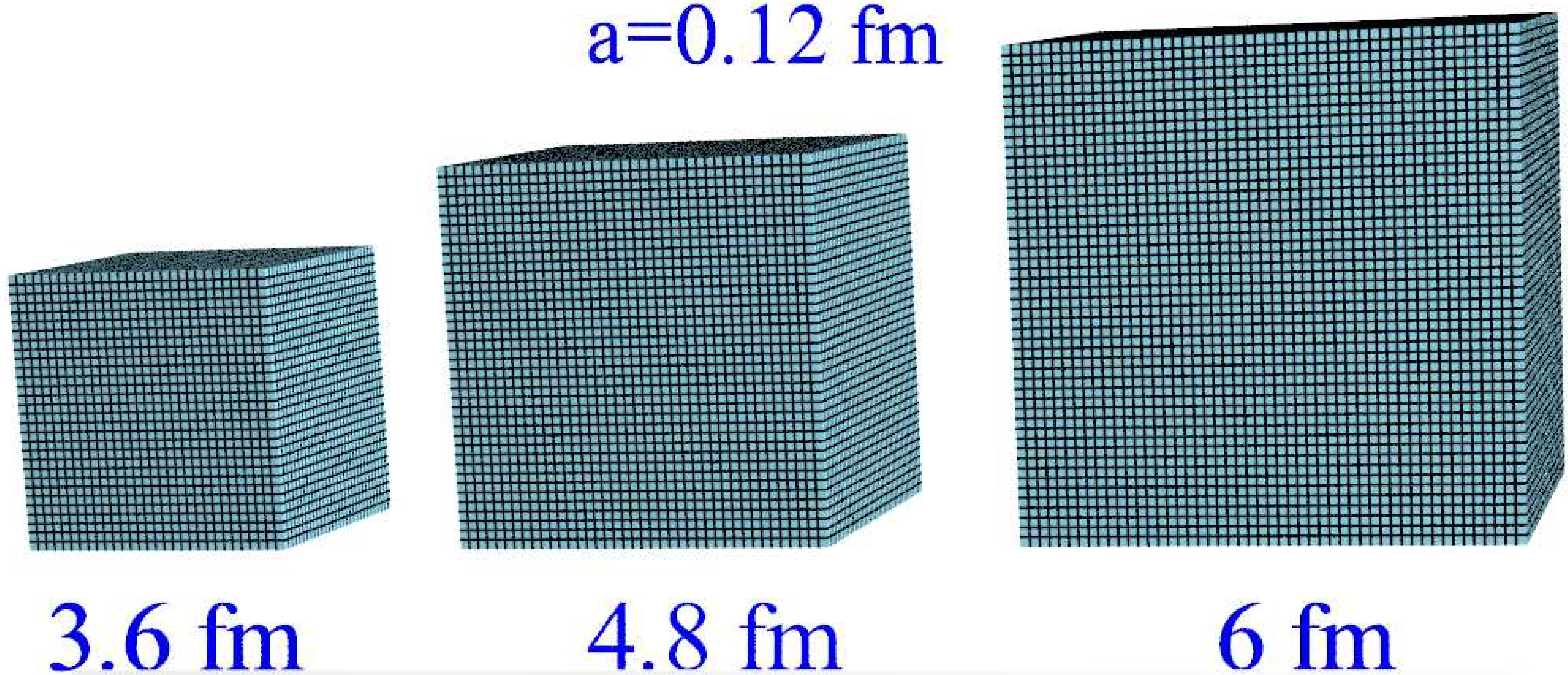
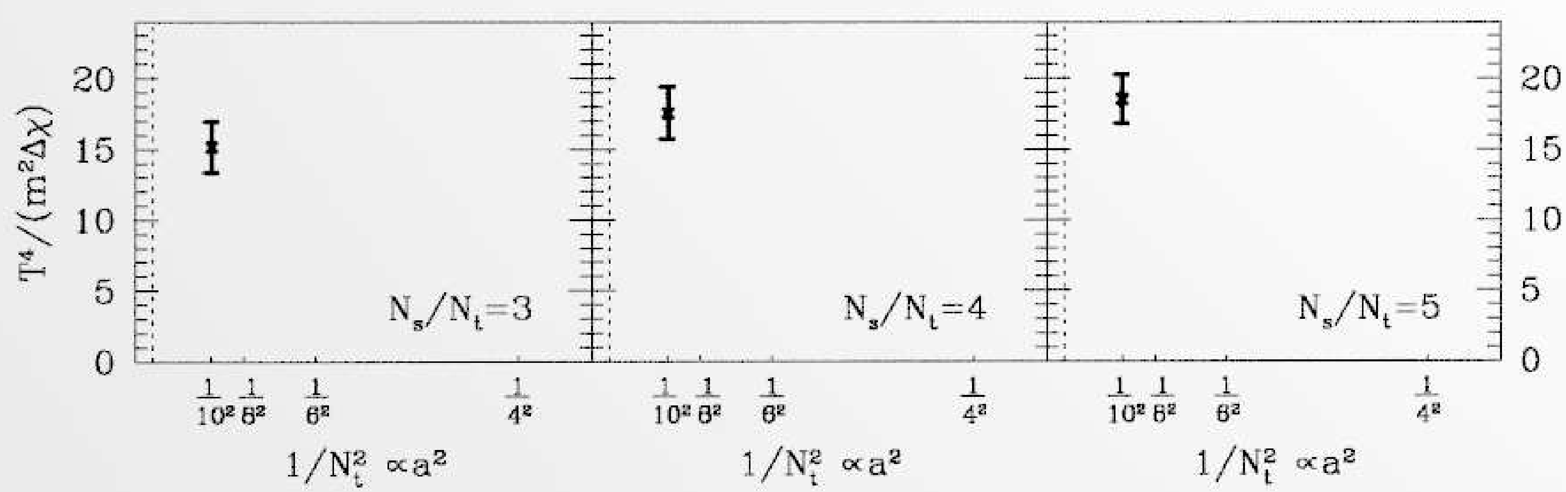
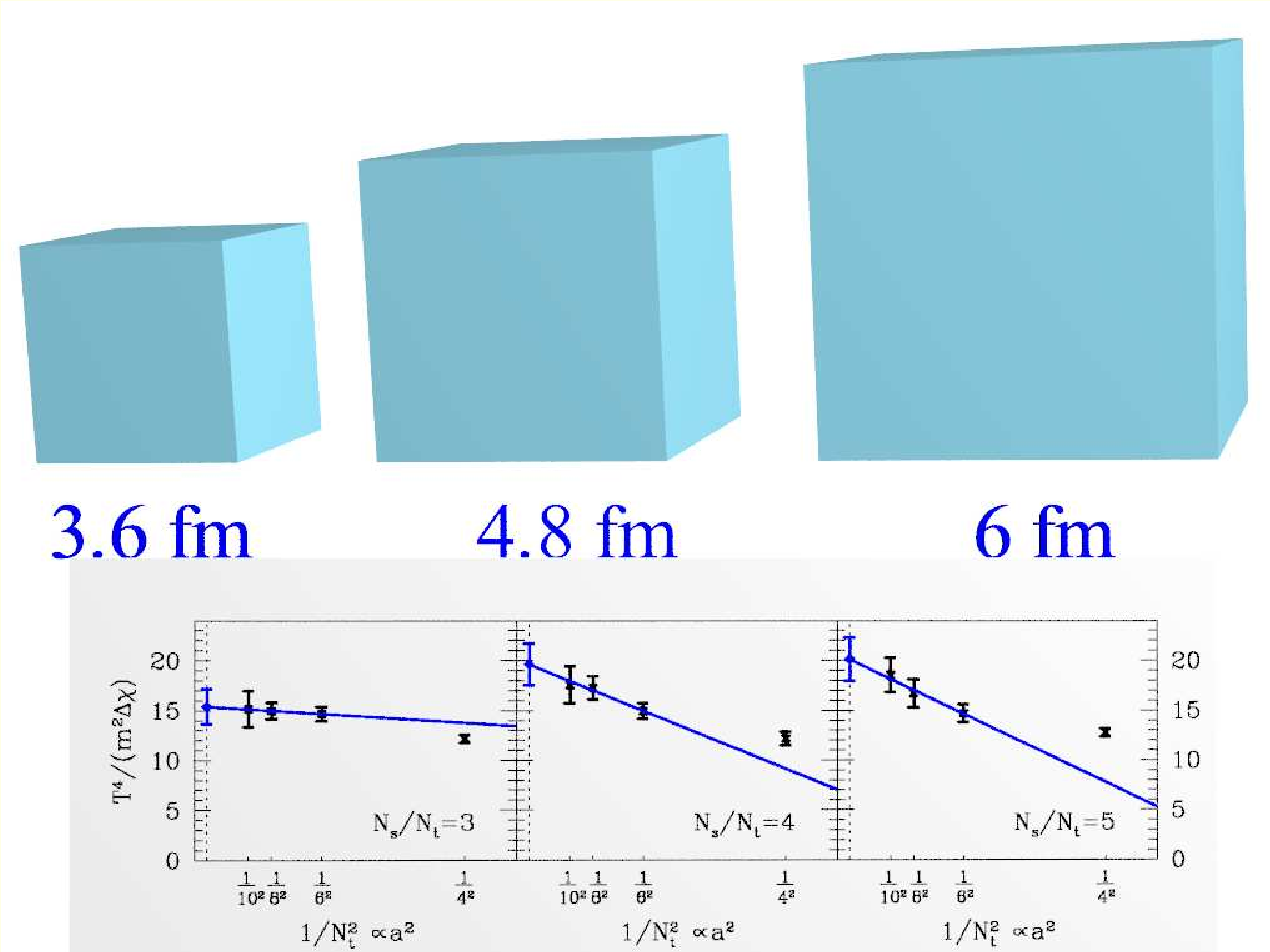
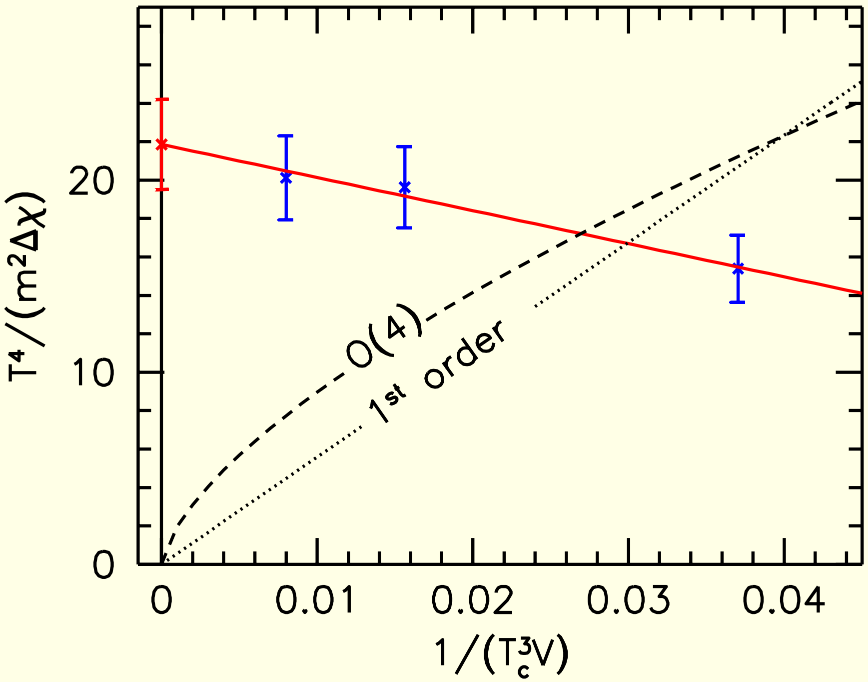



a=0.12 fm
3.6 fm
4.8 fm
6 fm


T⁴/(m²Δχ)
0
5
10
15
20
N_s/N_t=3
N_s/N_t=4
N_s/N_t=5
1/10²
1/8²
1/6²
1/4²
1/N_t² ∝a²


3.6 fm
4.8 fm
6 fm
$T^4/(m^2\Delta\chi)$
$N_s/N_t=3$
$N_s/N_t=4$
$N_s/N_t=5$
$1/N_t^2 \propto a^2$
$1/N_t^2 \propto a^2$
$1/N_t^2 \propto a^2$

• finite size scaling analysis with continuum extrapolated $m^2 \Delta\chi$



the result is consistent with an approximately constant behavior for a factor of 5 difference within the volume range

chance probability for 1/V is 10^{-19} for O(4) is $7 \cdot 10^{-13}$

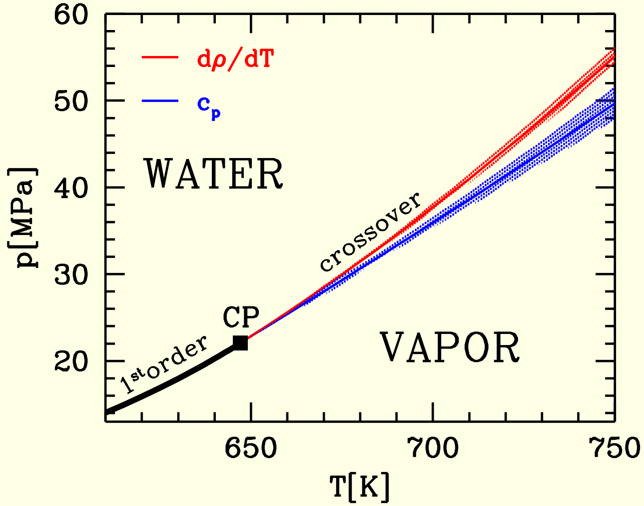
continuum result with physical quark masses in staggered QCD:

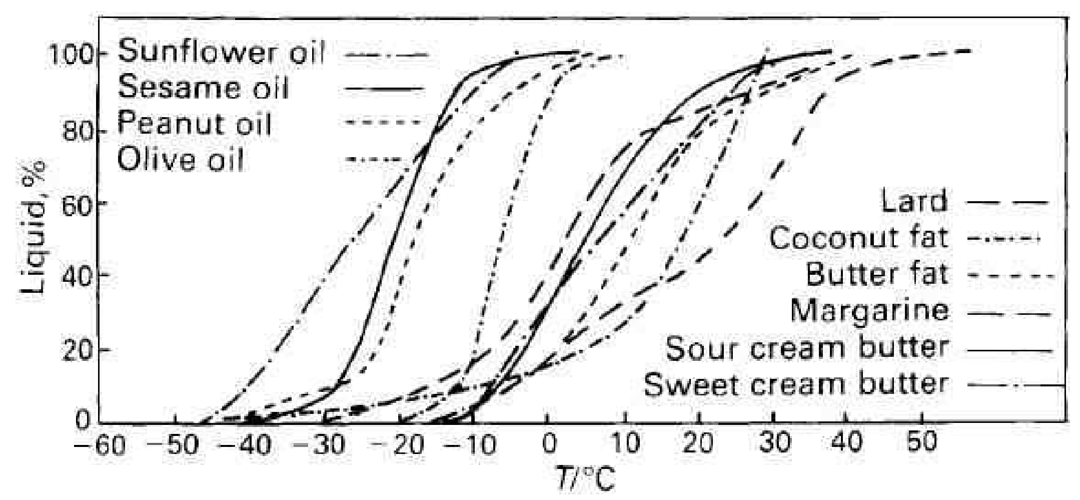
the QCD transition at μ=0 is a cross-over

The transition temperature (N_t=4,6,8,10)

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46 [hep-lat/0609068]

- a cross-over has no unique T_c: example of water-steam transition





above the critical point c_p and $d\rho/dT$ give different T_cs.

QCD: chiral & quark number susceptibilities or Polyakov loop

they result in different T_c values $\Rightarrow$ physical difference

extrapolations from large a: $\sigma, r_0, m_\rho, m_N, m_{K^*}, m_\Omega, f_\pi, f_K$: different a (in fm)

this lead to different T_c values $\Rightarrow$ non-physical ambiguity

will be removed in the continuum limit (most precise scale is set by f_K)

$T = 0$:

set the physical scale and locate the physical point

Three quantities are needed (m_π and m_K for the quark masses)

Several possibilities for the third quantity

- string tension (not existing in full QCD)
- static quark potential at intermediate distances ($r_0^2 \cdot dV/dr$=1.65)
- directly measurable quantities (e.g. f_K)

Further quantities are predictions (e.g. r_0, f_π, m_{K^*})

$T > 0$:

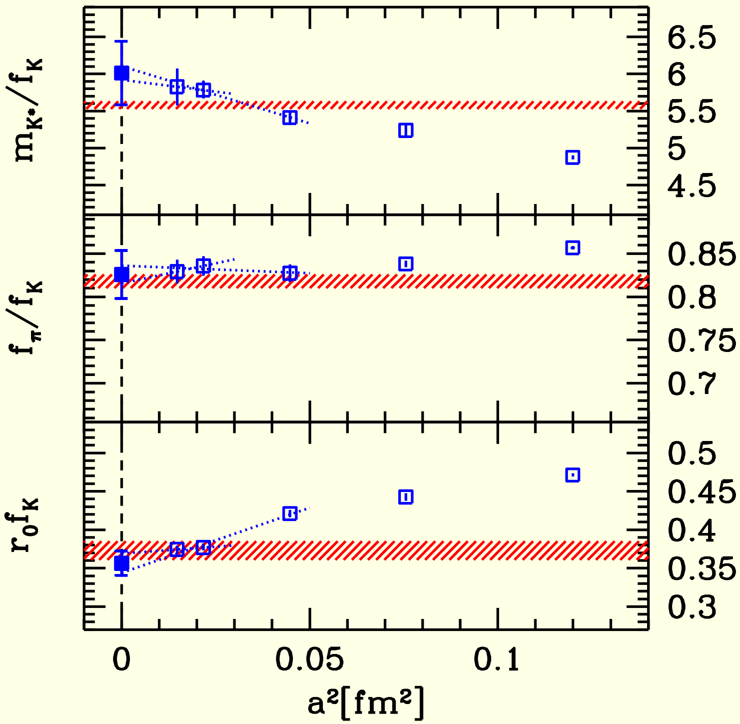
cross-over $\rightarrow$ different definitions give different T_c

Possible choices:

- Chiral susceptibility
- Quark number susceptibility
- Polyakov-loop

T=0 Simulations

- m_π, m_K and f_K was used to set the quark masses and scale
- $m_{ud} \approx 3, 5, 7, 9 \times m_{ud,phys}$ together with chiral extrapolation
- lattices from $12^3 \cdot 24$ up to $24^3 \cdot 32$



Predictions for m_{K^*}, f_π and consistent with experimental values
r_0 is consistent with MILC measurement

Chiral susceptibility:

Renormalization: seen before

Quark number susceptibility:

$$\frac{\chi_s}{T^2} = \frac{1}{TV}\frac{\partial^2 \log Z}{\partial \mu_s^2}\bigg|_{\mu_s=0}$$

No renormalization necessary

Polyakov loop:

$$P = \frac{1}{N_s^3}\sum_{\mathbf{x}} \mathrm{tr}[U_4(\mathbf{x},0)U_4(\mathbf{x},1)\ldots U_4(\mathbf{x},N_t-1)]$$

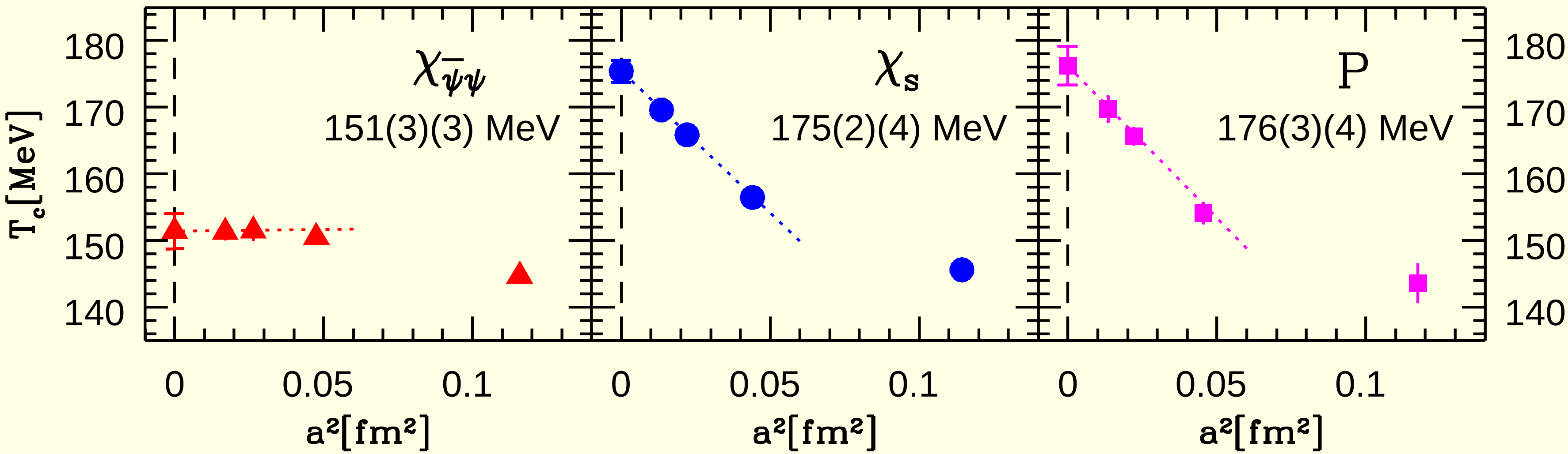
Related to the static quark free energy:

$$|\langle P\rangle|^2 = \exp(-\Delta F_{q\bar{q}}(r\rightarrow\infty)/T)$$

Renormalization condition for the potential: $V_R(r_0) = 0$

$$|\langle P_R\rangle| = |\langle P\rangle|\exp(V(r_0)/(2T))$$

Continuum extrapolations

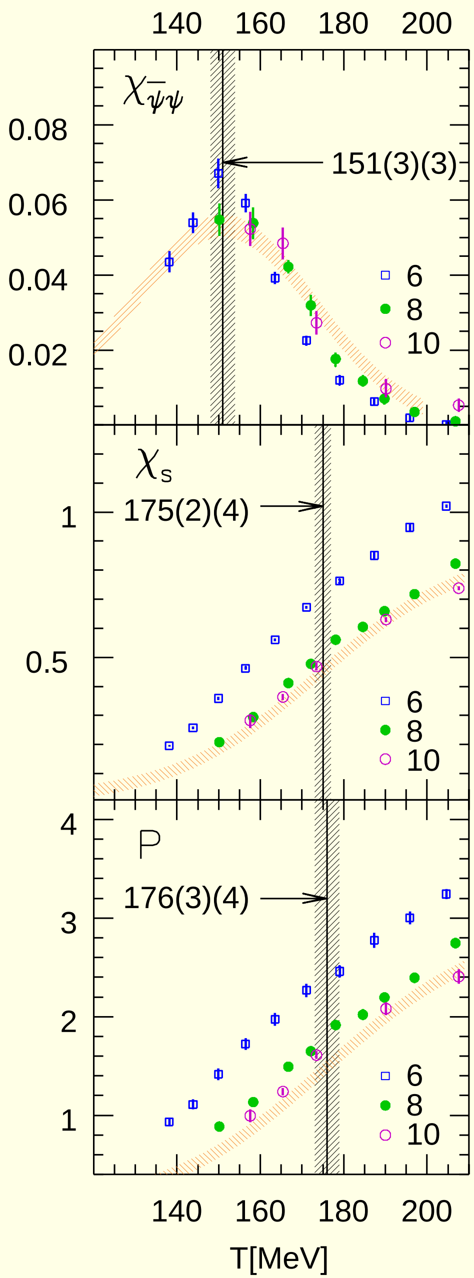


N_t=4 is off, N_t=6,8 and 10 show nice scaling for all quantities

Chiral and de-confinement transitions at different locations
25(4) MeV difference

Note: different normalization leads to different T_c
(e.g. $\Delta\chi/T^2$ leads to $\approx$10 MeV higher T_c)

$\rightarrow T_c(\Delta\chi)$ consistent with MILC '2004: $T_c = 169(12)(4)$
Their analysis used coarser lattices, non-physical quark masses, smaller aspect ratios and inexact R algorithm



Chiral susceptibility

T_c=151(3)(3) MeV

ΔT_c=28(5)(1) MeV

Quark number susceptibility

T_c=175(2)(4) MeV

ΔT_c=42(4)(1) MeV

Polyakov loop

T_c=176(2)(4) MeV

ΔT_c=38(5)(1) MeV

N_t=6,8,10 are in the a^2 scaling regime, N_t=8,10 are practically the same

- $T_c(\chi_{\bar{\psi}\psi})$ consistent with MILC '2004: $T_c = 169(12)(4)$ MeV

- BBCR collaboration: published result [M. Cheng et.al, Phys. Rev. D74 (2006) 054507]

Transition temperature from $\chi_{\bar{\psi}\psi}$ and Polyakov loop, from both quantities

T_c=192(7)(4) MeV, $\Longrightarrow$ for $\chi_{\bar{\psi}\psi}$ contradicts our result (≈40 MeV)

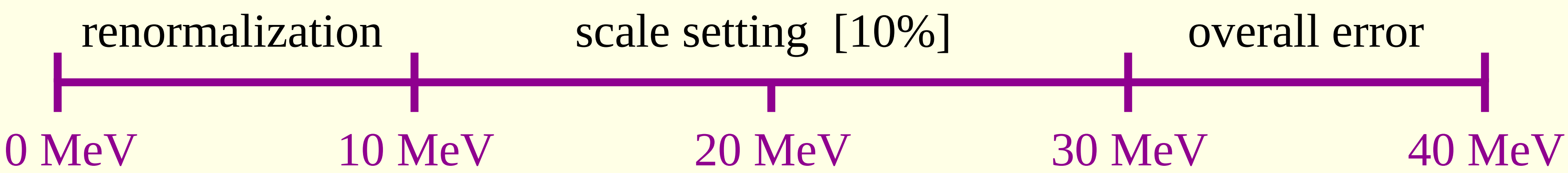
Main differences to our work

normalization changes T_c (multiply a Gaussian by T^2 $\Rightarrow$ peak shifts)

no renormalization, χ/T^2 is used: explains only ≈ 10 MeV difference

only $N_t = 4$ & 6 (cutoff: a ≈0.3 fm & 0.2 fm or a^{-1}≈700 MeV & 1 GeV)

scale is set by r_0 instead of f_K (influences only the overall accuracy)

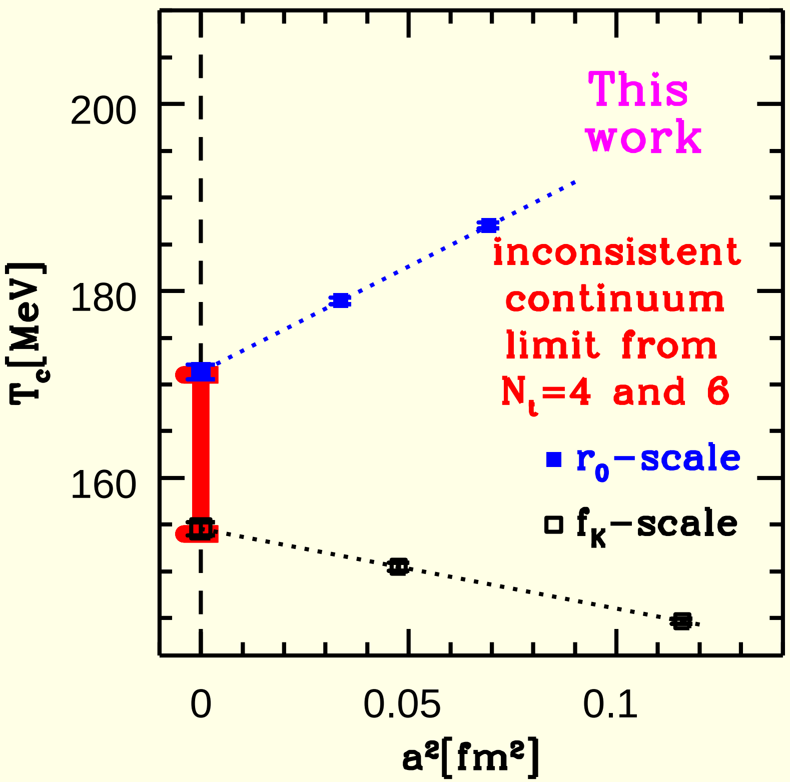


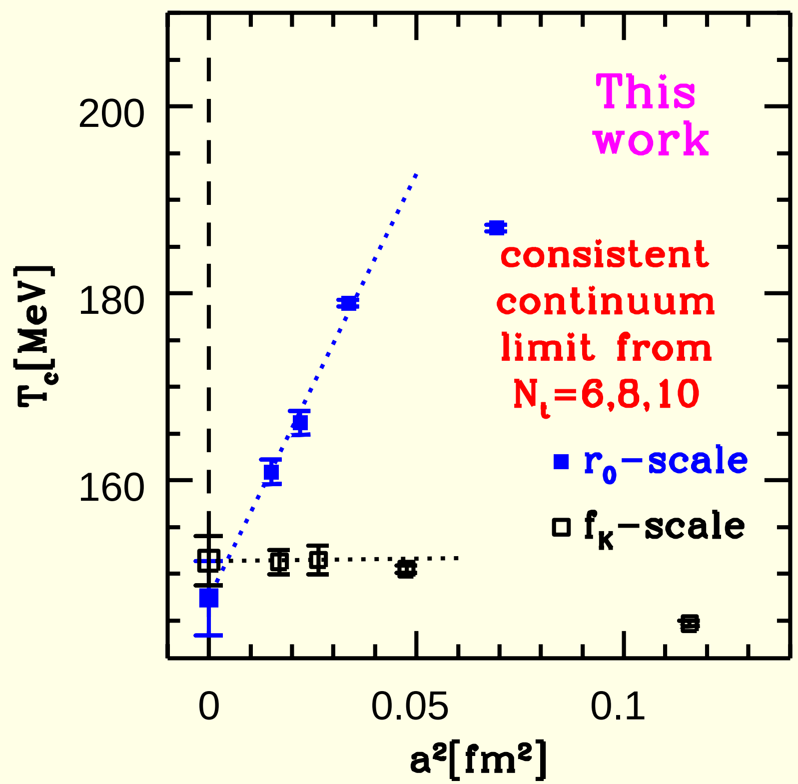
What is the reason for this discrepancy?

Their last concluding remark: it is desirable to

"obtain a reliable independent scale setting for the transition temperature from an observable not related to properties of the static potential".

What if one used the static potential (r_0) and f_K to set the scale?
compare N_t=4,6 and 4,6,8,10 extrapolations with different scale settings



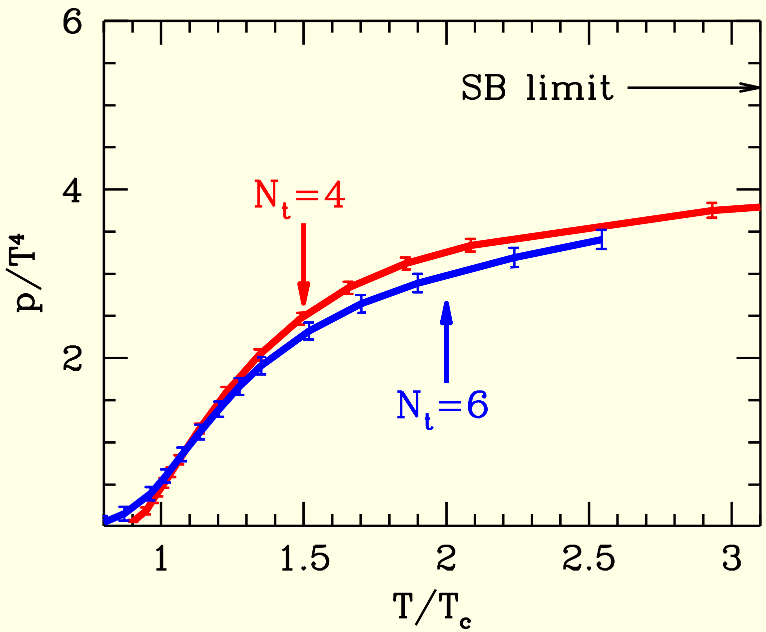


Continuum limits from $N_t = 4, 6$ are inconsistent, from $N_t = 6, 8, 10$ consistent
not surprising: eg. asqtad at $N_t \approx 10$ has $\approx$10% scale difference between r_1 & f_K
Lüscher (Dublin) & DelDebbio et al: a=.06fm $\approx$20% difference between r_0 & m_{K^*}

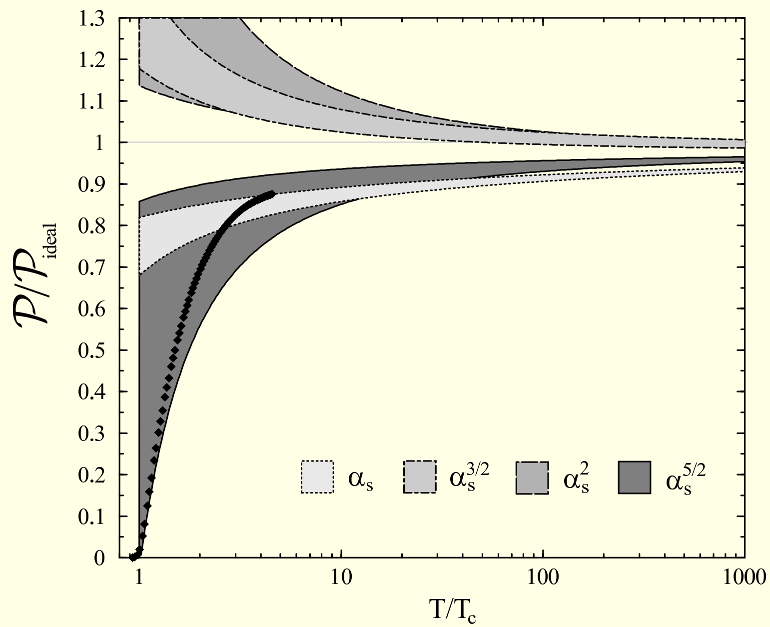
one needs 3 points in the scaling regime (2 points are always on a line)

Link to continuum perturbation theory: equation of state at large T

lattice results for the EoS extend upto a few times T_c



perturbative series "converges" only at asymptotically high T



- the standard technique is the integral method:

$\bar{p}$=T/V·log(Z), but Z is difficult $\Rightarrow$ $\bar{p}$ integral of (∂log(Z)/$\partial\beta$,∂log(Z)/∂m)
subtract the T=0 term, the pressure is given by: $p(T)=\bar{p}(T)-\bar{p}(T=0)$

- back of an envelope estimate:

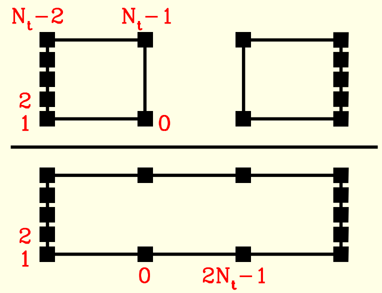
$T_c\approx$150–200 MeV, m_π=135 MeV and try to reach T=20·T_c for N_t=8 (a=0.0075 fm)
$\Rightarrow N_s$ > 4/m_π $\approx$ 6/T_c = 6·20/T = 6·20·N_t $\approx$ 1000 $\Rightarrow$ completely out of reach

a. subtract successively: $p(\mathrm{T})=\bar p(\mathrm{T})-\bar p(\mathrm{T}=0)=[\bar p(\mathrm{T})-\bar p(\mathrm{T}/2)]+[\bar p(\mathrm{T}/2)-\bar p(\mathrm{T}/4)]+\ldots$

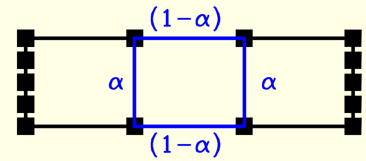
$\Longrightarrow$ for subtractions at most twice as large lattices are needed

b. instead of the integral method calculate: $\bar p(\mathrm{T})-\bar p(\mathrm{T}/2)=\mathrm{T}/(2\mathrm{V})\cdot\log[\mathrm{Z}^2(N_t)/\mathrm{Z}(2N_t)]$

$$\frac{Z^2(N_t)}{Z(2N_t)} =$$

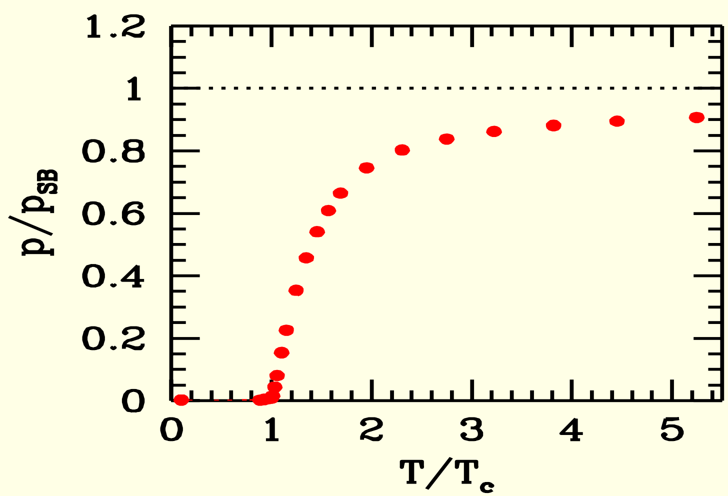


$$\bar{Z}(\alpha) =$$



define $\bar Z(\alpha)=\int \mathscr{D}U \exp[-\alpha \mathrm{S}_{1b}-(1-\alpha)\mathrm{S}_{2b}] \Longrightarrow \mathrm{Z}^2(N_t)=\bar Z(0)$ and $\mathrm{Z}(2N_t)=\bar Z(1)$

one gets directly $\bar p(\mathrm{T})-\bar p(\mathrm{T}/2)=\mathrm{T}/(2\mathrm{V})\int_0^1 d\log[\bar Z(\alpha)]/d\alpha\cdot d\alpha=\mathrm{T}/(2\mathrm{V})\int_0^1\langle \mathrm{S}_{1b}-\mathrm{S}_{2b}\rangle_\alpha\cdot d\alpha$



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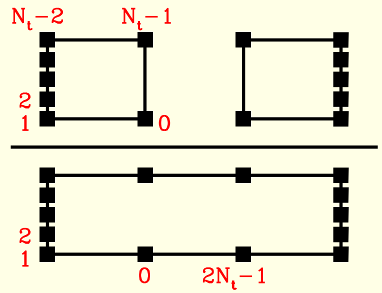

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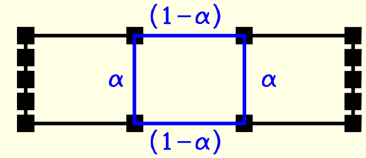

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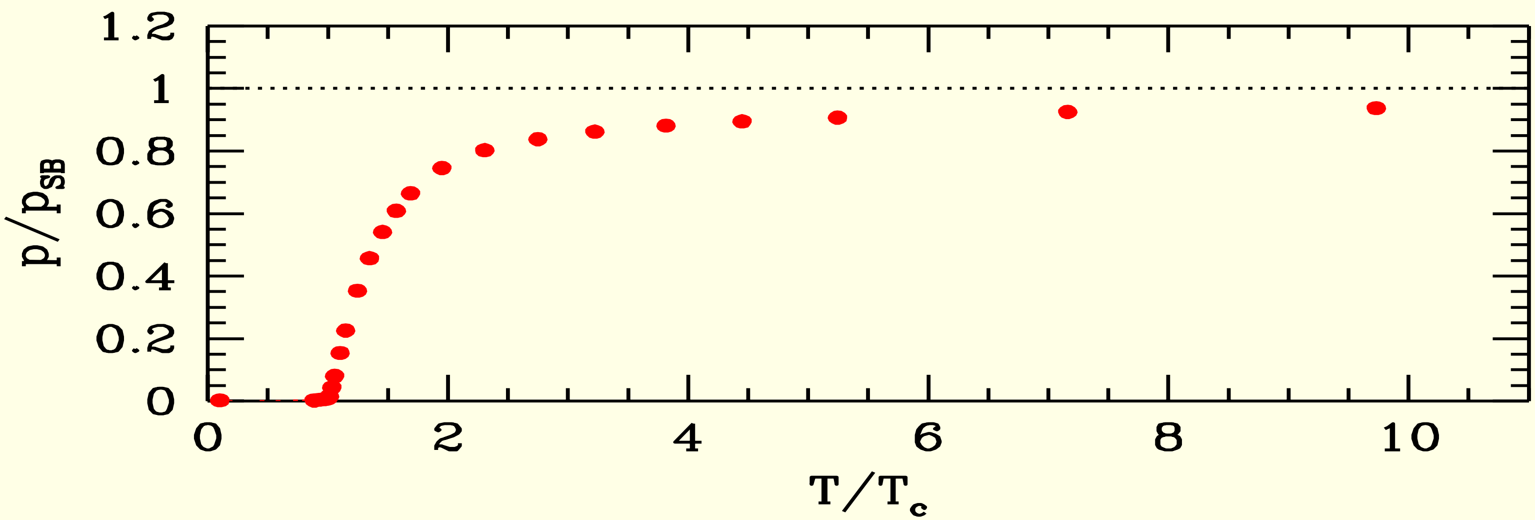

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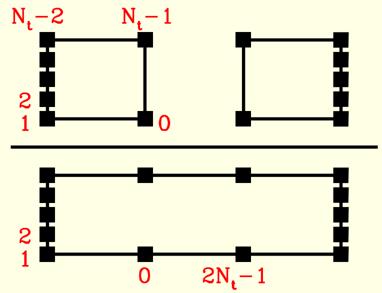

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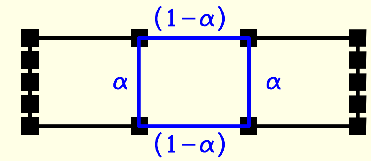

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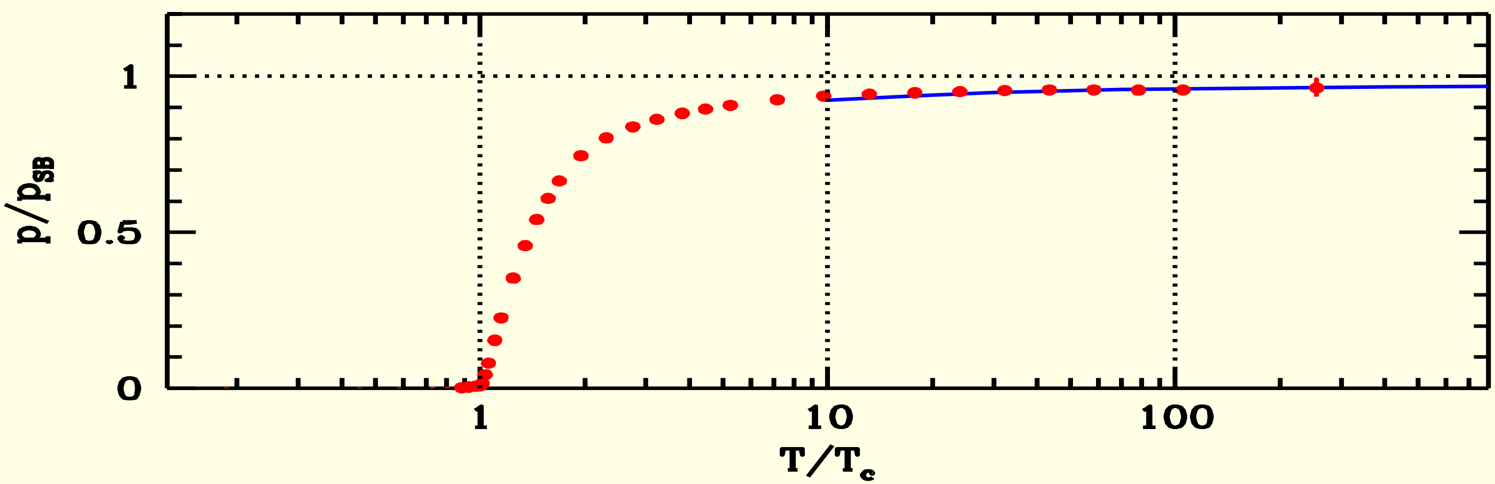

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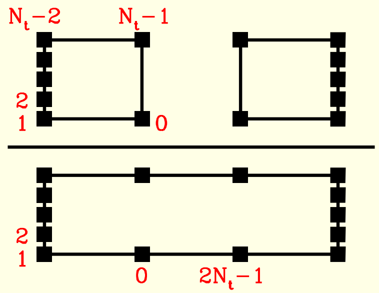

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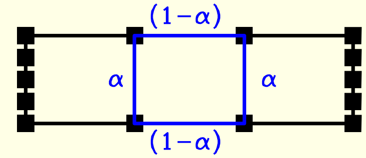
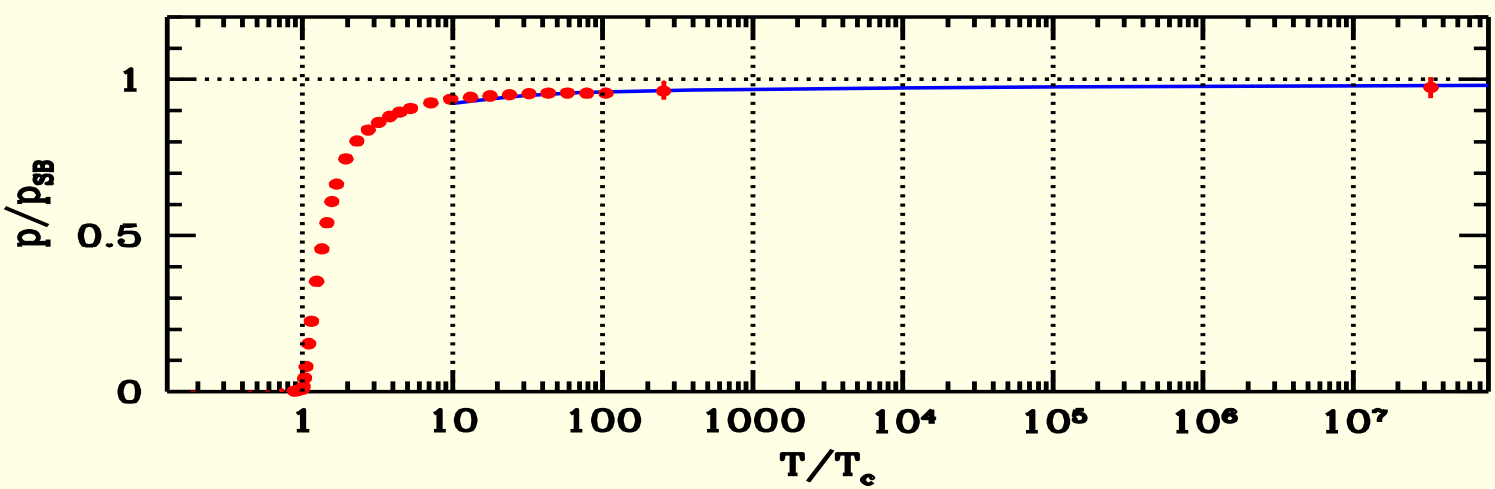


define $\bar{Z}(\alpha)=\int \mathscr{D}U \exp[-\alpha S_{1b}-(1-\alpha)S_{2b}] \Longrightarrow Z^2(N_t)=\bar{Z}(0)$ and $Z(2N_t)=\bar{Z}(1)$

one gets directly $\bar{p}(\mathrm{T})-\bar{p}(\mathrm{T}/2)=\mathrm{T}/(2\mathrm{V})\int_0^1 \mathrm{d}\log[\bar{Z}(\alpha)]/\mathrm{d}\alpha\cdot \mathrm{d}\alpha=\mathrm{T}/(2\mathrm{V})\int_0^1\langle S_{1b}-S_{2b}\rangle_\alpha\cdot \mathrm{d}\alpha$



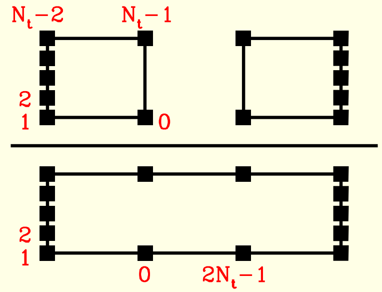
long awaited link between lattice thermodynamics and pert. theory is there

a. substract successively: $p(\mathrm{T}) = \bar{p}(\mathrm{T}) - \bar{p}(\mathrm{T}=0) = [\bar{p}(\mathrm{T}) - \bar{p}(\mathrm{T}/2)] + [\bar{p}(\mathrm{T}/2) - \bar{p}(\mathrm{T}/4)] + \ldots$

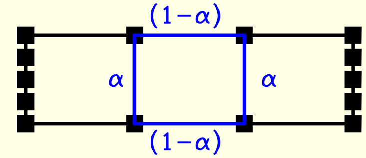
$\Longrightarrow$ for substractions at most twice as large lattices are needed

b. instead of the integral method calculate: $\bar{p}(\mathrm{T}) - \bar{p}(\mathrm{T}/2) = \mathrm{T}/(2\mathrm{V}) \cdot \log[\mathrm{Z}^2(N_t)/\mathrm{Z}(2N_t)]$

$$\frac{Z^2(N_t)}{Z(2N_t)} =$$

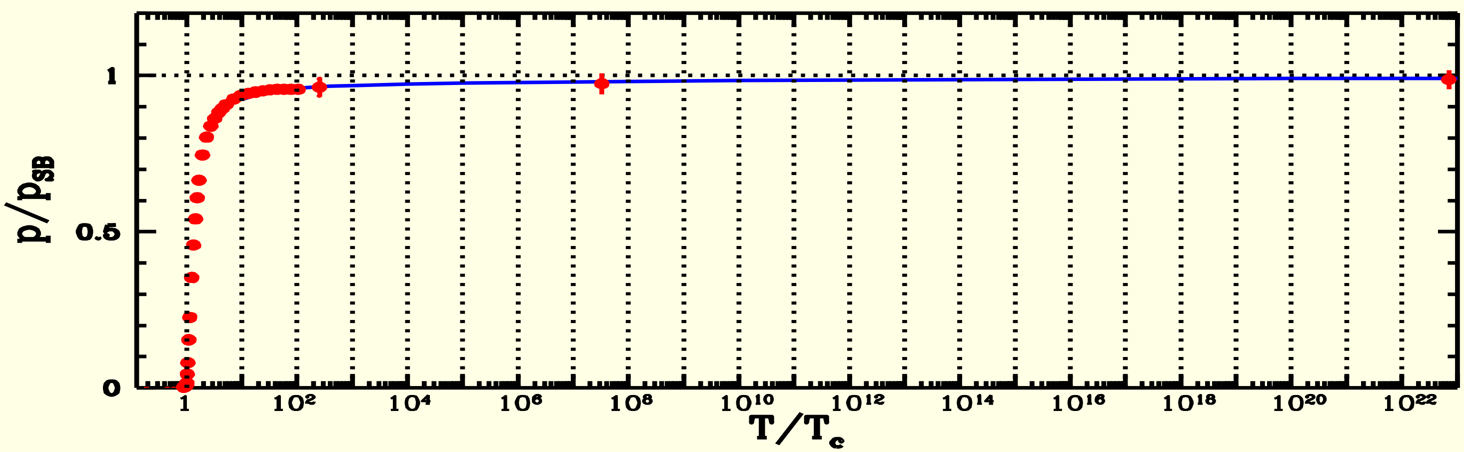


$$\bar{Z}(\alpha) =$$



define $\bar{Z}(\alpha) = \int \mathscr{D}U \exp[-\alpha S_{1b} - (1-\alpha) S_{2b}] \Longrightarrow Z^2(N_t) = \bar{Z}(0)$ and $Z(2N_t) = \bar{Z}(1)$

one gets directly $\bar{p}(\mathrm{T}) - \bar{p}(\mathrm{T}/2) = \mathrm{T}/(2\mathrm{V}) \int_0^1 \mathrm{d}\log[\bar{Z}(\alpha)]/\mathrm{d}\alpha \cdot \mathrm{d}\alpha = \mathrm{T}/(2\mathrm{V}) \int_0^1 \langle S_{1b} - S_{2b} \rangle_\alpha \cdot \mathrm{d}\alpha$



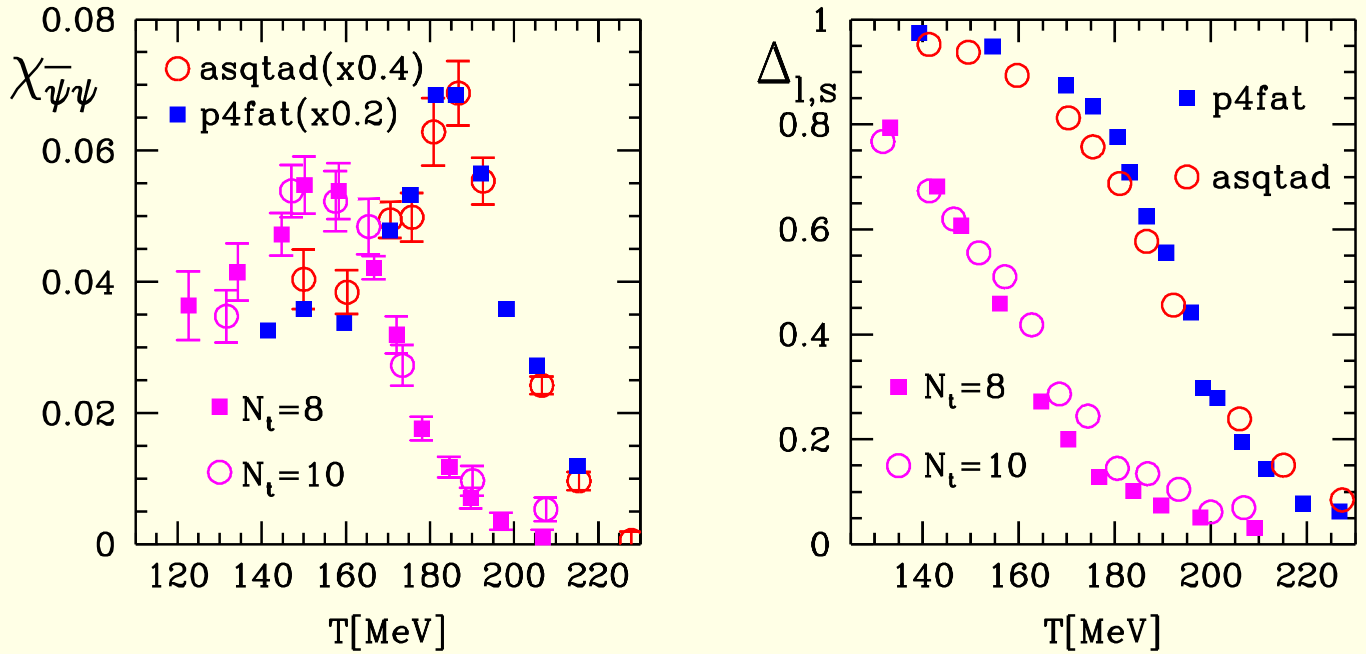
long awaited link between lattice thermodynamics and pert. theory is there

G.Endrodi, Z.Fodor, S.D.Katz, K.K.Szabo, arXiv:0710.4197

hotQCD collaboration: new results ⇒ differences/problems remained (1)

hotQCD: [0710.1655, 0711.0661, 0804.4148, RBRC workshop 04.08]

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46 (magenta points)



chiral susceptibility, rescaled (quark masses are different)

$$\chi_{\bar\psi\psi} = m_l^2 \frac{\partial^2}{\partial m_l^2}\left(f(T) - f(T=0)\right)$$

chiral condensate

$$\Delta_{l,s} = \left(\langle \bar{l}l\rangle - m_l/m_s\langle \bar{s}s\rangle\right) / \left(\langle \bar{l}l\rangle_{T=0} - m_l/m_s\langle \bar{s}s\rangle_{T=0}\right)$$

Another difference/problem is related to the width (2)

there is no phase transition, only an analytic cross-over
$\Longrightarrow$ different definitions lead to different temperature scales

our claim:
Polyakov-loop, strange number susceptibility inflection points give quite higher T_c (175 MeV) than the chiral susceptibility peak (151 MeV)

hotQCD claim:
"no large differences in the transition temperature from observables related to deconfinement and chiral symmetry restoration, both lie in the range T=(185-195) MeV" 0711.0661

due to crossover 'Problem 2.' is less severe as 'Problem 1.',
even in our case it is possible to define chiral/deconfinement operators with same transition temperatures e.g. by multiplying by some powers of T

Possible resolutions

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46 [hep-lat/0609068]

$N_t = 4,6$ of 'p4fat3' are too coarse, no controlled continuum limit

status 2008: fine $N_t = 8$ somewhat better but still large discrepancy

our simulations:

• scale set by f_K, non-Goldstone pions distort chiral extrapolation or continuum limit

• naive staggered dispersion relation has large artefacts

hotQCD:

• nonphysical quark masses $\to \sim$ 5 MeV Soeldner's talk at Lattice'08

• scale set by $r_0^{\mathrm{HPQCD,UKQCD}}$=0.469(7) fm

r_0^{ETM}=0.444(4) fm, r_0^{QCDSF}=0.467(6) fm, $r_0^{\mathrm{PACS-CS}}$= 0.492(6)(+7) fm

both:

• universality problem of staggered discretization

• bug in computer code

• ...

maybe a bit of all

systematic errors are simply underestimated

Improving our previous results

1. improving $T = 0$ simulations

previously: $m_\pi \geq 240$MeV + chiral extrapolations

now: $\boxed{m = m^{\rm phys}}$, no need for chiral extrapolations

$\Rightarrow$ more precise scale/renormalization

2. improving $T > 0$ simulations

previously: $N_t = 4, 6, 8, 10$ at the physical point

now: $\boxed{N_t = 12}$ at the physical point

$\Rightarrow$ more control over lattice artefacts

Simulation setup: T>0, machine

nVidia GeForce 8800 Ultra
768 MB video memory
103.7 GB/sec bandwidth
two cards per machine

multishift inverter on $12 \cdot 36^3$ fits to the video memory and runs with 32 Gflop
gauge force on the video card: 15 Gflop

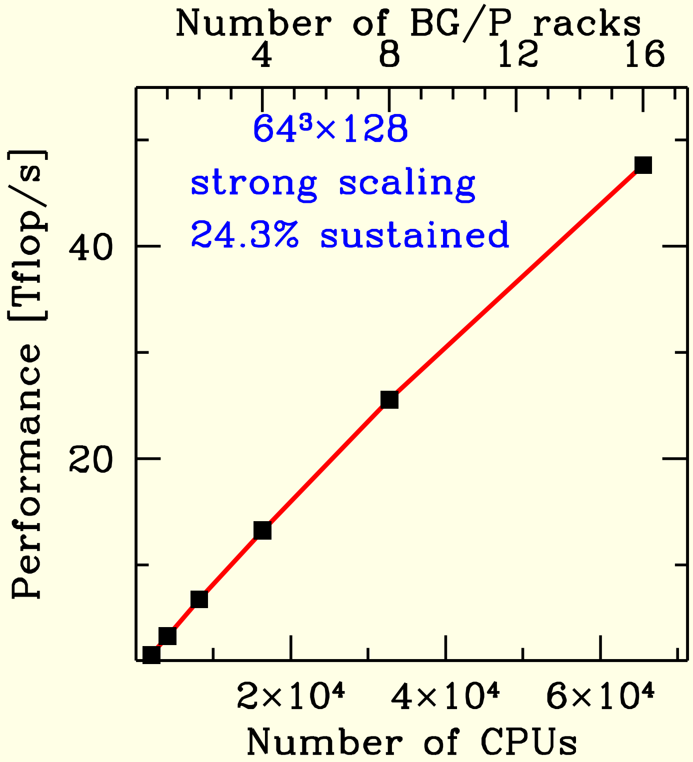
only single precision arithmetics, HMC-force is not needed more precisely,
for HMC-energy mixed precision inverters ($\varepsilon = 10^{-8}$)

100 GPU-s in dual PC's in Wuppertal $\rightarrow$ 3 Tflops $\sim$ 1 BGP rack
cluster computing: ideal for finite T with many parameter sets

Simulation setup: T=0, machine

zero T lattices are too large for a single video card

→ BG/P supercomputer in Juelich



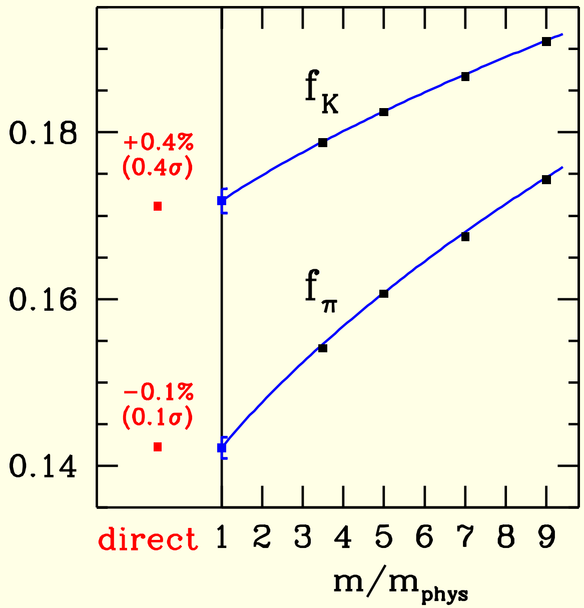
Simulation setup: T=0, volumes and statistics

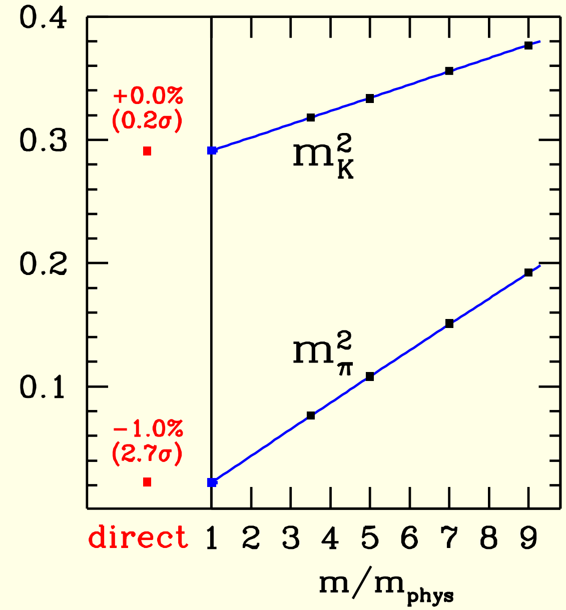
simulations directly at the physical point

choose lattice sizes, so that finite volume corrections are below 0.5% for f_π, m_π, f_K, m_K (cont. formula of Colangelo, Durr, Haefeli '05)

β	N_t^{crit}	lattice	#traj
3.45	~ 4	$24^3 \times 32$	1500
3.55	~ 6	$24^3 \times 32$	3000
3.67	~ 8	$32^3 \times 48$	1500
3.75	~ 10	$40^3 \times 48$	1500
3.85	~ 13	$48^3 \times 64$	1500

T=0 results at the physical point, pseudoscalars





chiral extrapolations (not staggered χPT !) work amazingly well

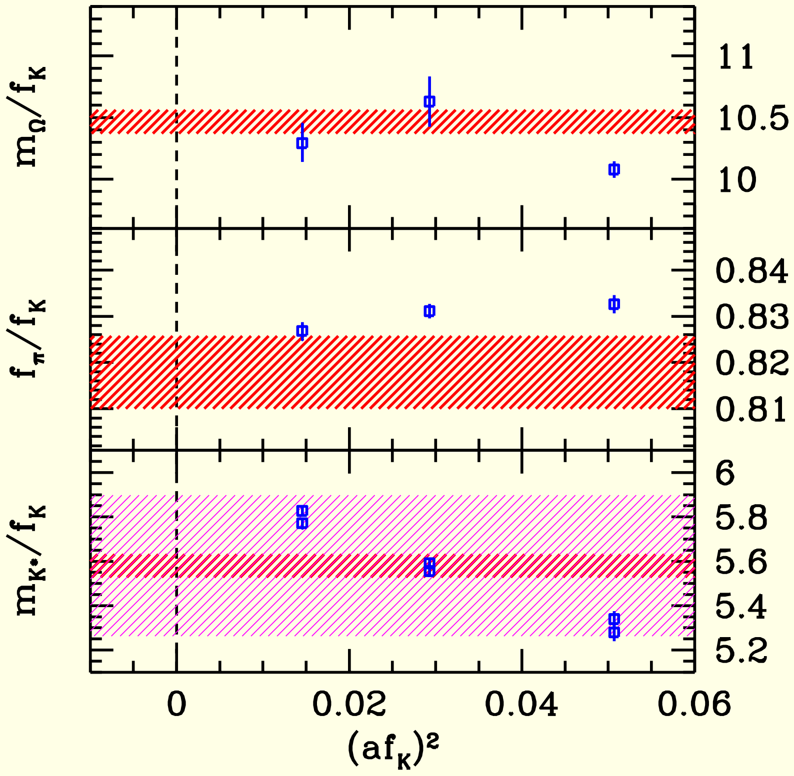
for all analyzed spacings the extrapolation error for f_π, m_π, f_K, m_K is $\leq$ 1%

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46 [hep-lat/0609068]

"2% is the accuracy of our LCP."

T=0 results at the physical point, scale setting

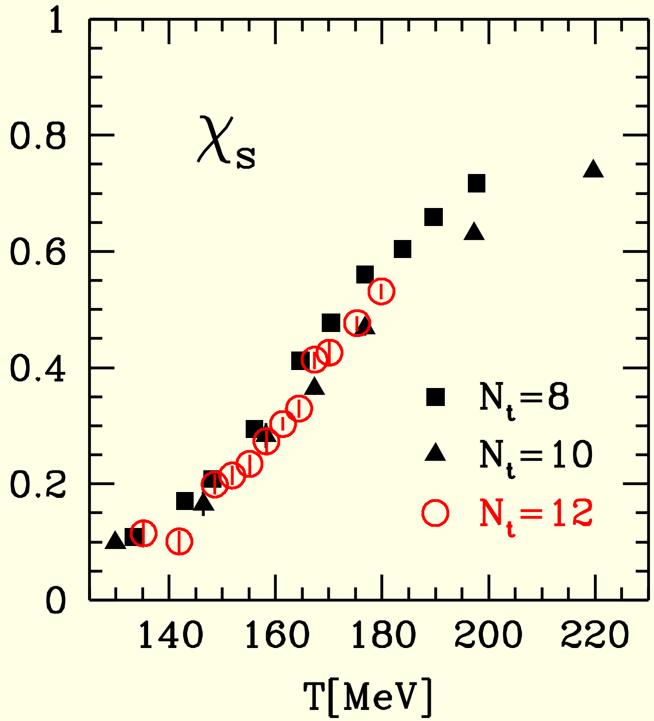
last concluding remark of our competitors: it is desirable to
"obtain a reliable independent scale setting for the transition temperature from an observable not related to properties of the static potential".



extend original f_K scale setting to m_Ω, f_π, m_{K^*} $\Rightarrow$ consistent scales
red bands are the experimental values with uncertainties
K^* decays in the physical point, width is also given (pink)
smaller spacings and r_0 are currently under analysis

T>0 results

strange quark number susceptibility

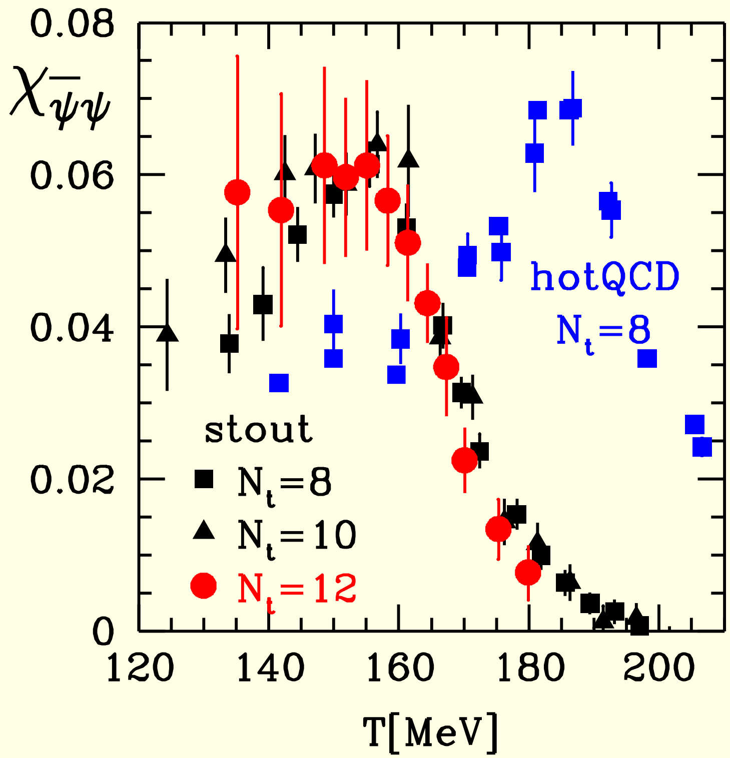


preliminary results, 300-500 trajectories in each point
good agreement with old $N_t = 10$ data

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46 [hep-lat/0609068]
"For the transition temperature in the continuum limit one gets: $T_c(\chi_s) = 175(2)(4)$ MeV"

T>0 results

renormalized chiral susceptibility



nice agreement with old $N_t = 8, 10$ data

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46 [hep-lat/0609068]

"the transition temperature based on the chiral susceptibility reads $T_c(\chi_{\bar{\psi}\psi}) = 151(3)(3)$ MeV"

• universality problem in 2+1 flavour staggered QCD

naively discretizing fermions leads to 16 degenerate fermions
staggered fermions on 2^4 cell leads to 4 degenerate fermions
take the root of the fermion determinant to reach $2+1$ flavours

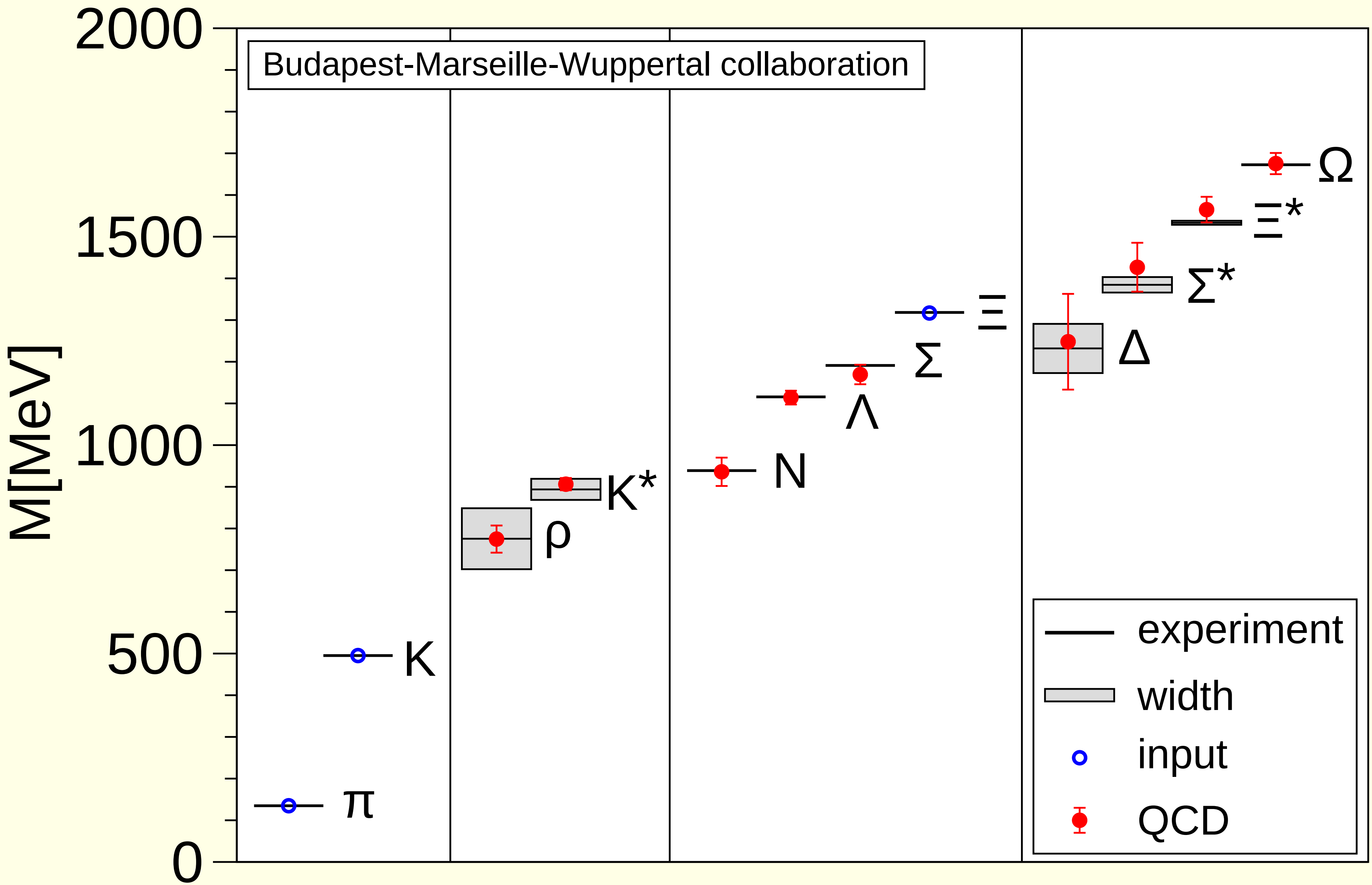
known to be non-local for any non-vanishing lattice spacings

much faster than any other fermion formulation
the largest scale thermodynamics projects are all in staggered QCD

lively discussion: staggered fermions are good, bad or just ugly

new algorithms for Wilson fermions (in the universality class of QCD)

one can already control all systematics
lattice spacings, quark masses, finite volume within really n_f=2+1 QCD



⇒ use a formulation, which is known to be in the universality class of QCD

Summary

• The nature of the QCD transition was determined

we used physical quark masses and extrapolated to the continuum limit

$\Longrightarrow$ the QCD transition is an analytic cross-over

• The transition temperature is determined (2006)

Chiral susceptibility:

T_c=151(3)(3) MeV, ΔT_c=28(5)(1) MeV

Quark number susceptibility:

T_c=175(2)(4) MeV, ΔT_c=42(4)(1) MeV

Polyakov loop:

T_c=176(2)(4) MeV, ΔT_c=38(5)(1) MeV

• Gap between lattice and perturbative bulk thermodynamics

two new methods to reach (arbitrary) high temperatures

connection to perturbation theory is established

• hotQCD:
they improved their T>0 simulations from N_t=4,6 to N_t=8

• our group:
we improved our T=0 simulations with physical quark masses
we improved our T>0 simulations from N_t=6,8,10 to $N_t = 12$

our chiral extrapolations were correct on the 1% level
consistent scales obtained by f_K, m_Ω, f_π and m_{K^*} (we will give r_0 in fm)

preliminary results for chiral susceptibility and strange susceptibility
$N_t = 12$ are in good agreement with our 2006 results

• discrepancies are not resolved
should we use N_t=16? No, the accumulated data is most probably enough
should hotQCD use other scale settings, too? Probably yes (was their plan)

• n_f=2+1 staggered QCD can be influenced by the universality problem
$\Rightarrow$ use a formulation, which is known to be in the universality class of QCD
recent algorithmic developments allow one to use Wilson fermions