Hot QCD

Frithjof Karsch, BNL

- Introduction:

  deconfinement and chiral symmetry restoration

- The transition temperature in (2+1)-flavor QCD

- Bulk thermodynamics

- Conclusions

Deconfinement and χ-symmetry

- The chiral phase transition (i.e. at $m_q = 0$) is deconfining
  - true in QCD, i.e. SU(3) + fermions in the fundamental representation
  - SU(3) + fermions in the adjoint representation: $T_{deconf} < T_\chi$
- The transition in QCD with physical quark masses is a crossover

In which sense is the transition

deconfining and chiral symmetry restoring?

  - deconfinement: heavy hadrons $\Rightarrow$ light quarks and gluons; liberation of many new light degrees of freedom
    $\Rightarrow$ rapid change in ϵ/T^4, s/T^3, ...
  - chiral symmetry restoration: vanishing mass splittings, no new degrees of freedom
    $\Rightarrow$ minor effect on bulk thermodynamics, but rapid change of chiral condensate

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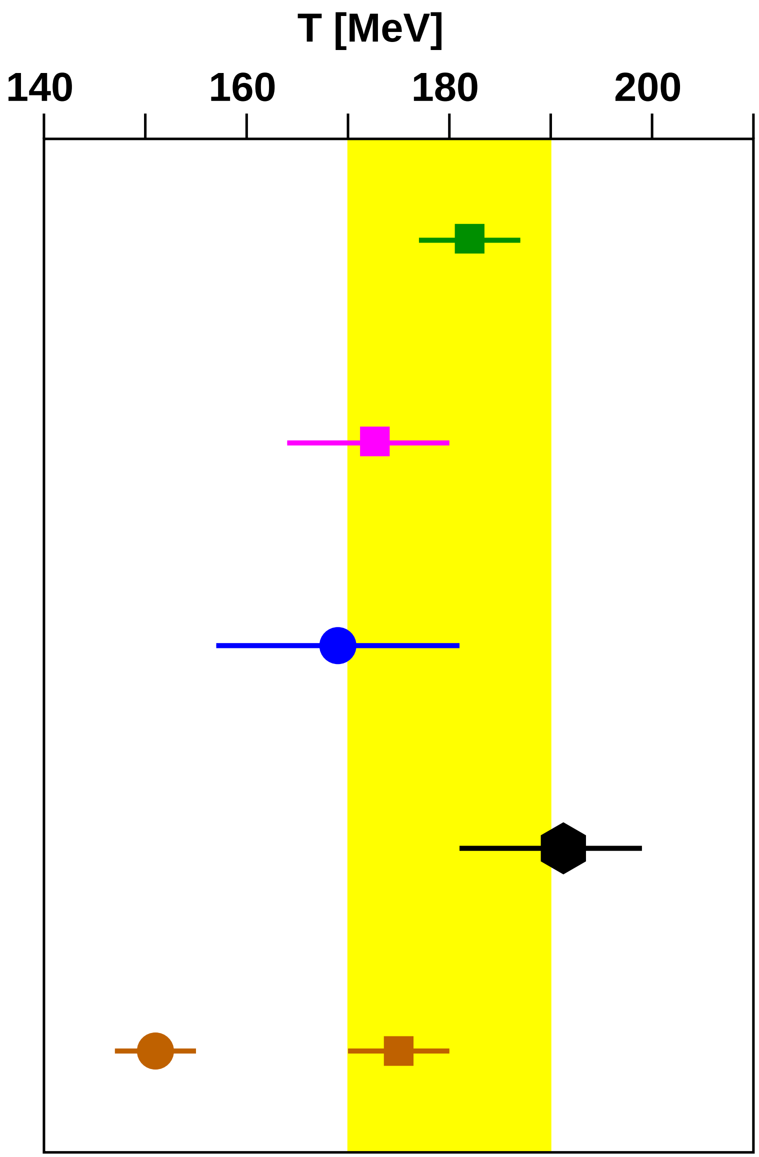
Summary of recent results on T_c



use T=0 scale: r0=0.469fm

Nf=2:

V.G. Bornyakov et al, POS Lat2005, 157 (2006)
(improved Wilson, Nt=8, 10; input: r0=0.5 fm)
(added Nt=12, Lattice'07) **(rescaled to r0)**

Y. Maezawa et al., hep−lat/0702005 (QM'2006)
(improved Wilson, Nt=4, 6; input: m−rho)
(no cont. exp. yet)

Nf=2=1:

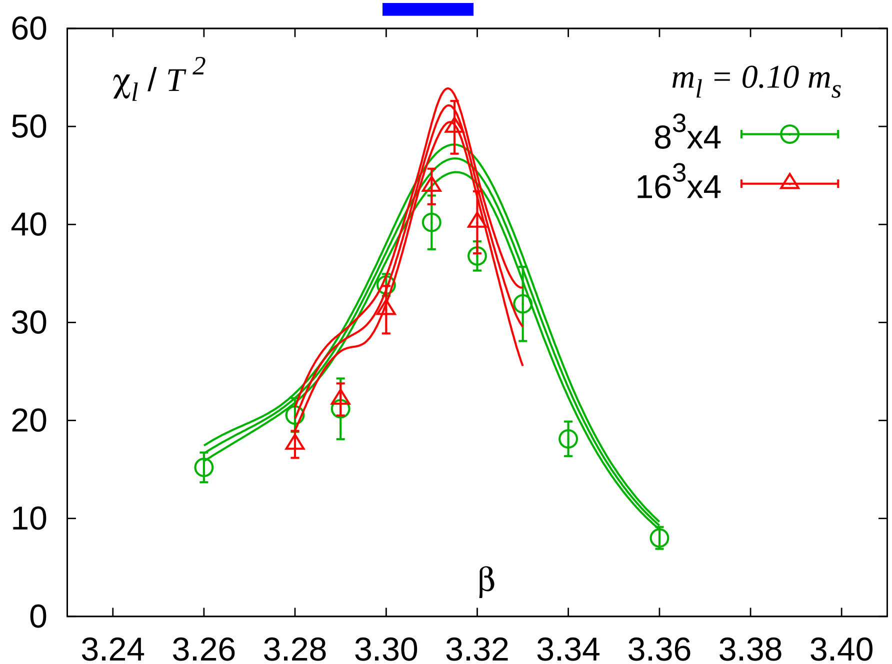
C. Bernard et al., Phys.Rev. D71, 034504 (2005)
(improved staggered (asqtad), Nt=4,6,8, input r1)
(rescaled to r0)

M. Cheng et al., Phys.Rev D74, 054507 (2006)
(improved staggered (p4), Nt=4,6; input r0)

Y. Aoki et al., Phys. Lett. B643, 46 (2006)
(staggered (stout), Nt=4,6,8,10; input fK)
(converted to r0)

Susceptibilities: χ_l, χ_L

2.5% error band ⇔ 5 MeV



disconnected part of chiral susceptibility

χ-sym. condens. fluct.

data sample for
$m_q = 0.1 m_s$
on $16^3 \times 4$ lattice

β	no. of conf.
3.2800	20510
3.2900	30160
3.3000	36100
3.3100	40440
3.3150	45570
3.3200	32310

M. Cheng et al (RBC-Bielefeld), PRD74, 054507 (2006)

200,000/10 trajectories enter Ferrenberg-Swendsen sample

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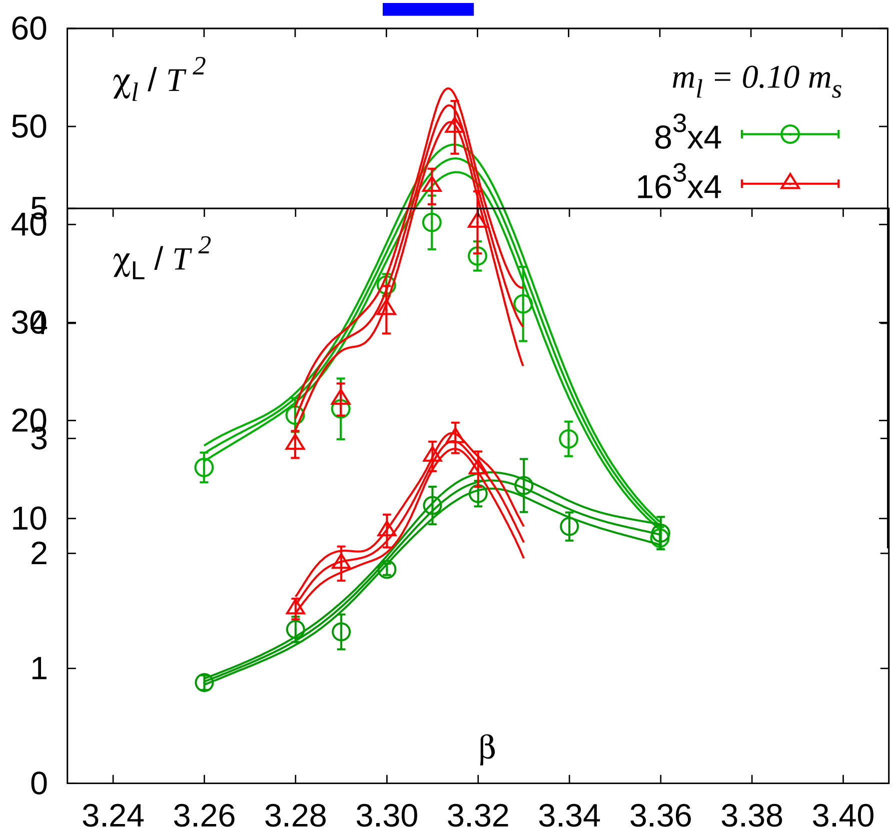

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Polyakov loop susceptibility

M. Cheng et al (RBC-Bielefeld), PRD74, 054507 (2006)

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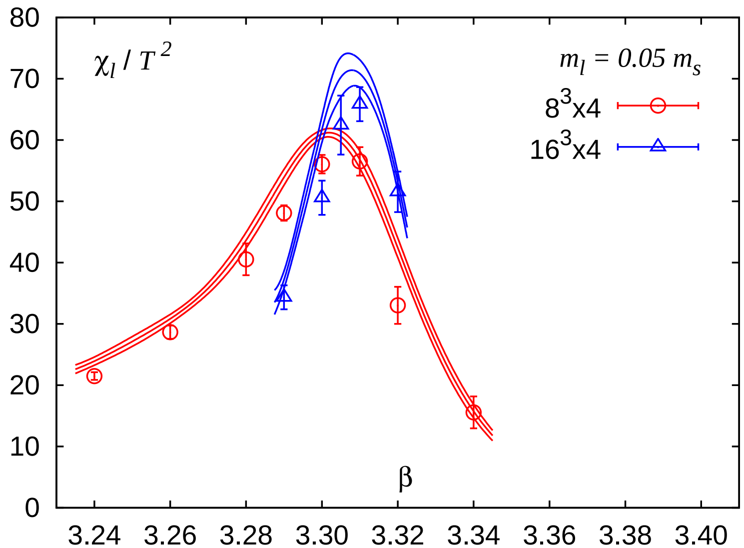
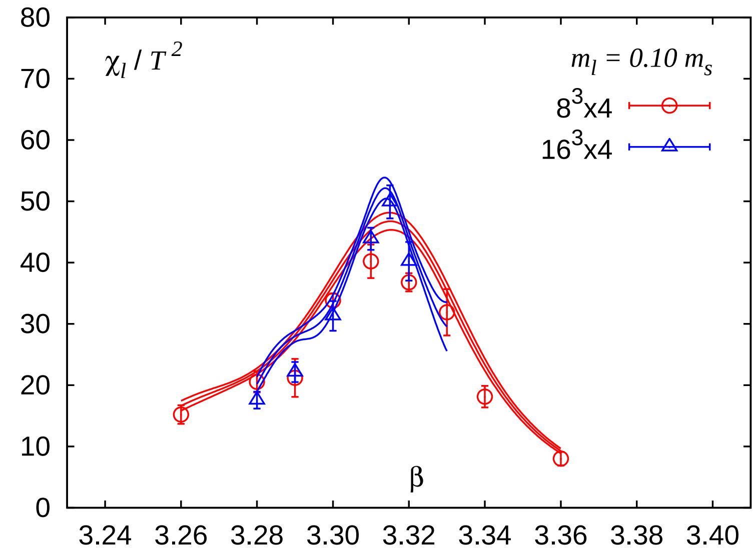
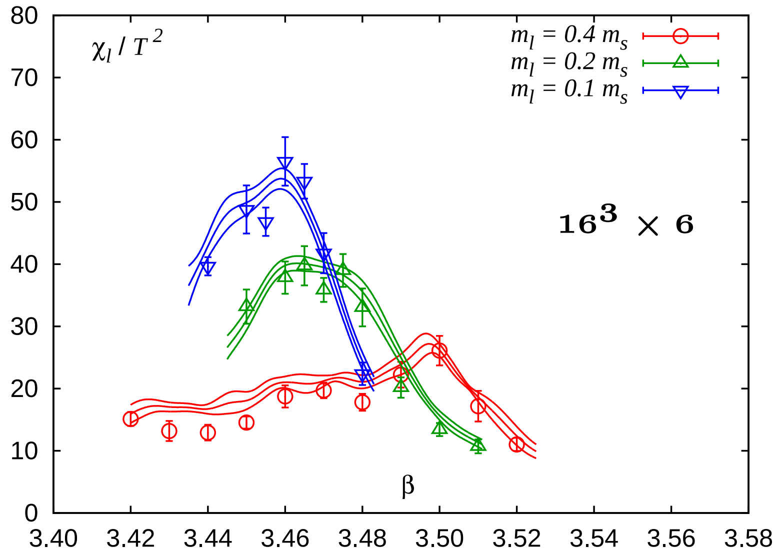
Chiral susceptibility, $N_\tau = 4,\ 6$



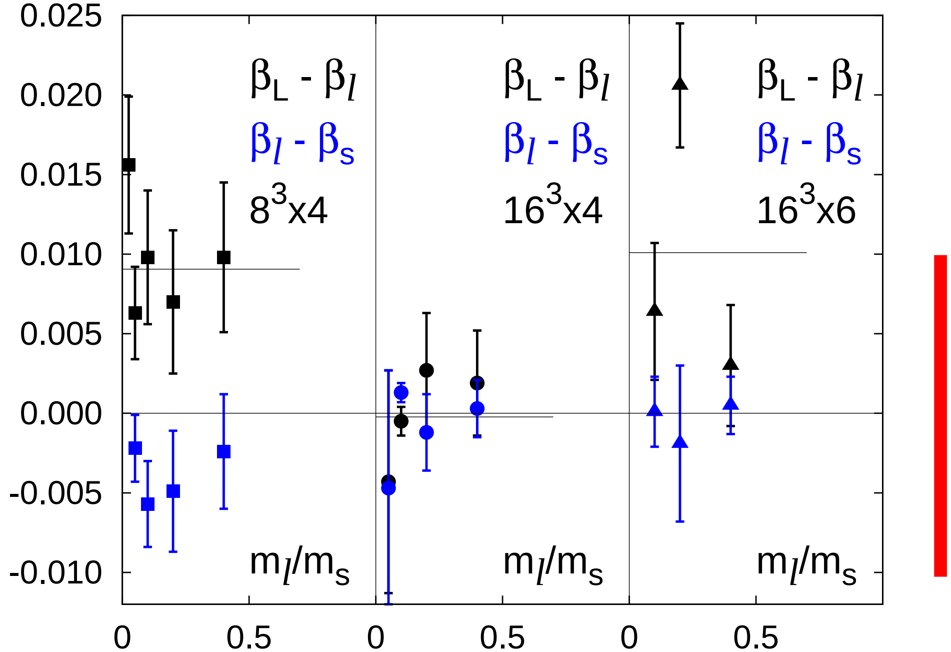




- weak volume dependence
- peak location consistent with that of Polyakov loop susceptibility and maximum of quartic fluctuation of quark number density

Ambiguities in locating the crossover point

differences of pseudo-critical couplings locating peaks in light (β_l), strange (β_s) and Polyakov loop (β_L) susceptibilities



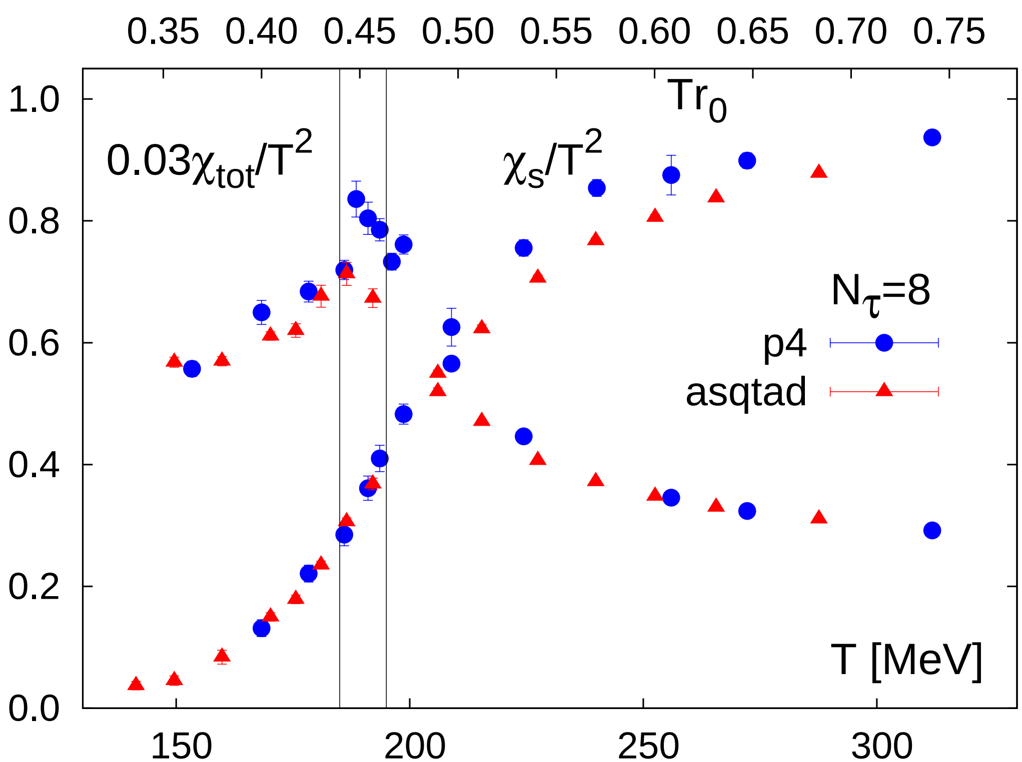
2.5% ($N_\tau = 4$) or 4% ($N_\tau = 6$) error band $\Leftrightarrow$ 5 or 8 MeV

differences in the location of pseudo-critical couplings are taken into account as systematic error

Deconfinement and χ-symmetry

- hotQCD, preliminary results for $32^3 \times 8$, $m_q = 0.1 m_s$

  consistent with RBC-Bielefeld: $16^3 \times 4$ and $24^3 \times 6$, $m_q = 0.1 m_s$



strange quark number susceptibility
and
chiral susceptibility

- inflection points difficult to quantify;
  would like to see c_4 (!!)
- consistent transition regions for
  χ_{tot} and χ_s
- no indication for 'low' chiral
  transition temperature

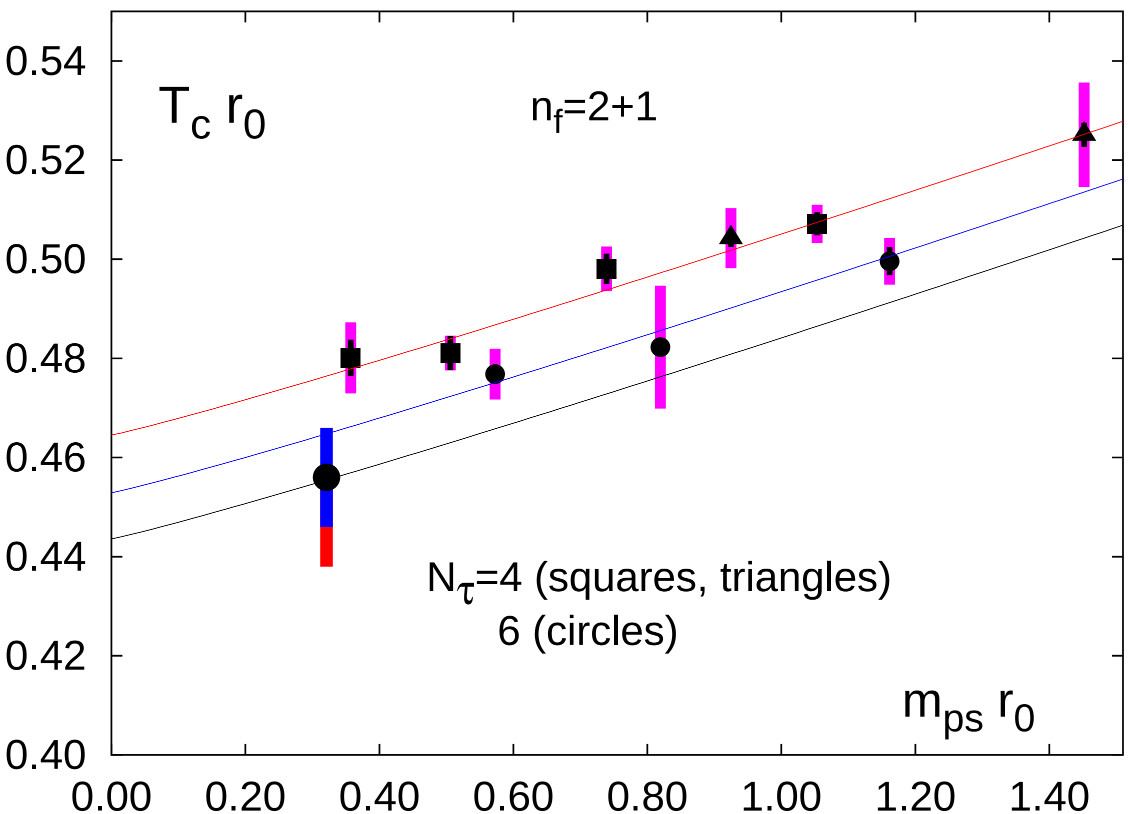
hotQCD talks by:
Rajan Gupta
Carleton DeTar

$T_c r_0$: continuum and quark mass extrapolation

extrapolation to chiral and continuum limit

$$(r_0 T_c)_{N_\tau} = (r_0 T_c)_{cont.} + b\,(m_{PS} r_0)^d + c/N_\tau^2$$

(d=1.08 (O(4), 2nd ord.), d=2 (1st ord.))



$\Rightarrow\ r_0 T_c = 0.456(7)^{+3}_{-1}$

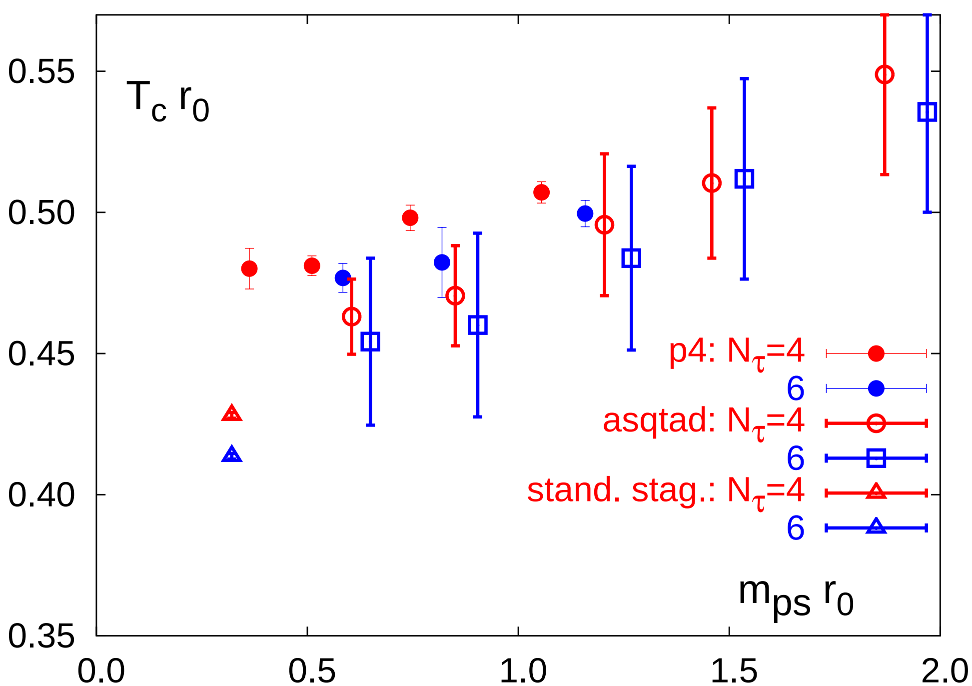
at phys. point

$\Rightarrow\ T_c = 192(7)(4)$ MeV

(1st error: β_c and r_0; 2nd error: N_τ^{-2} extrapolation)

Transition temperature: $N_\tau = 4, 6$

- RBC-Bielefeld (p4fat3 (p4)) vs. MILC (asqtad (Naik)) and Wuppertal (stout (stand. staggered))
- asqtad results for $N_\tau = 4$ and 6 agree with p4 results within statistical errors; (C.Bernard et al., PR D71, 034504 (2005))
- results obtained with stout action for $N_\tau = 4$ and 6 are about 15% lower; β_c from $N_\tau = 8, 10$ covers $(151 - 176)$ MeV; (Y. Aoki et al., hep-lat/0609068)



asqtad data for $T_c r_1$ rescaled with $r_0/r_1 = 1.4795$

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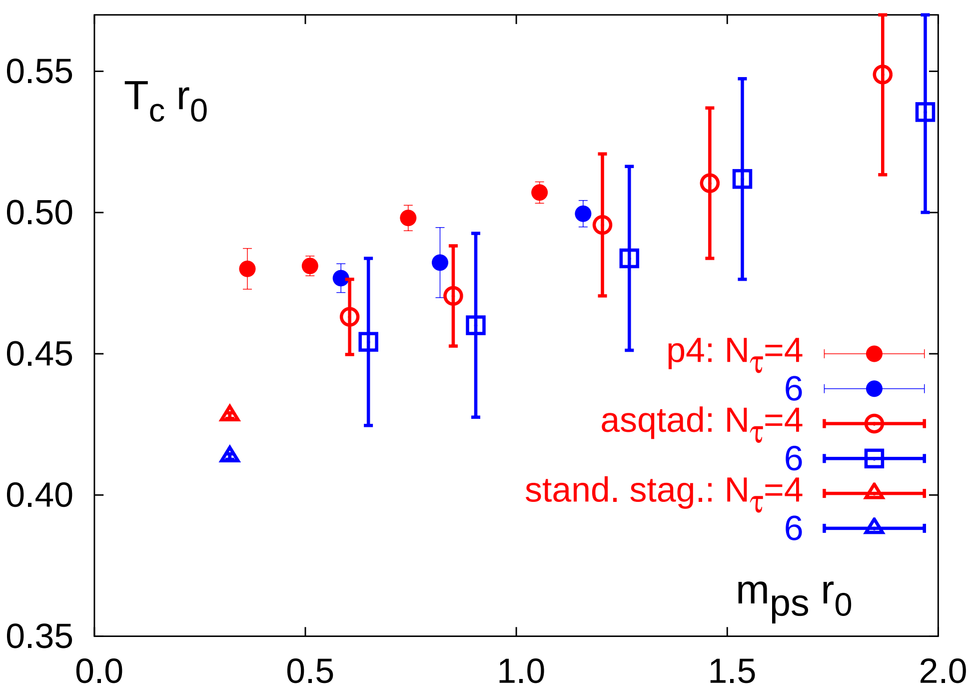

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asqtad: continuum extrapolation:

quoted T_c from $m_q/m_s \leq 1$ and fit in m_π/m_ρ yields

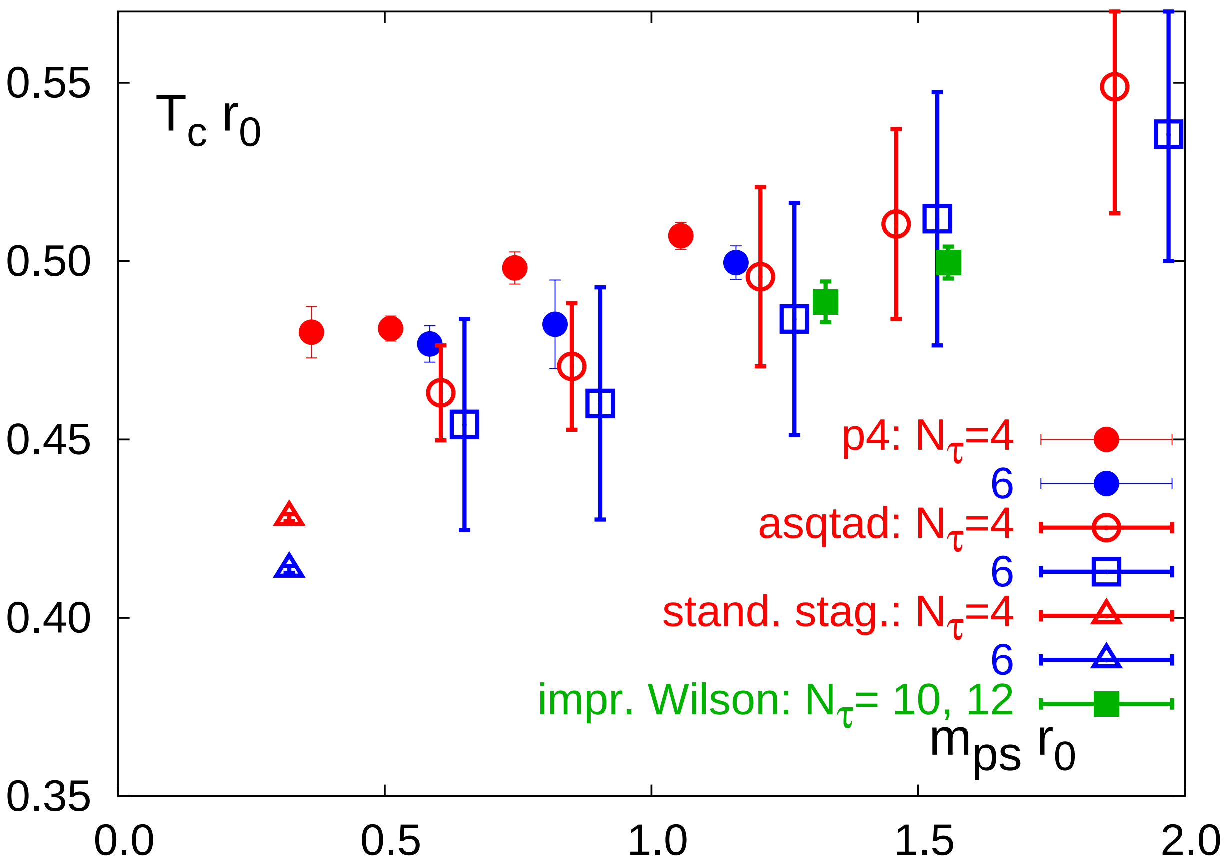
$T_c = 169(12)(4)$ MeV

using $m_q/m_s \leq 0.4$ and fit in $m_\pi r_0$ yields

$T_c = 173(13)(4)$ MeV

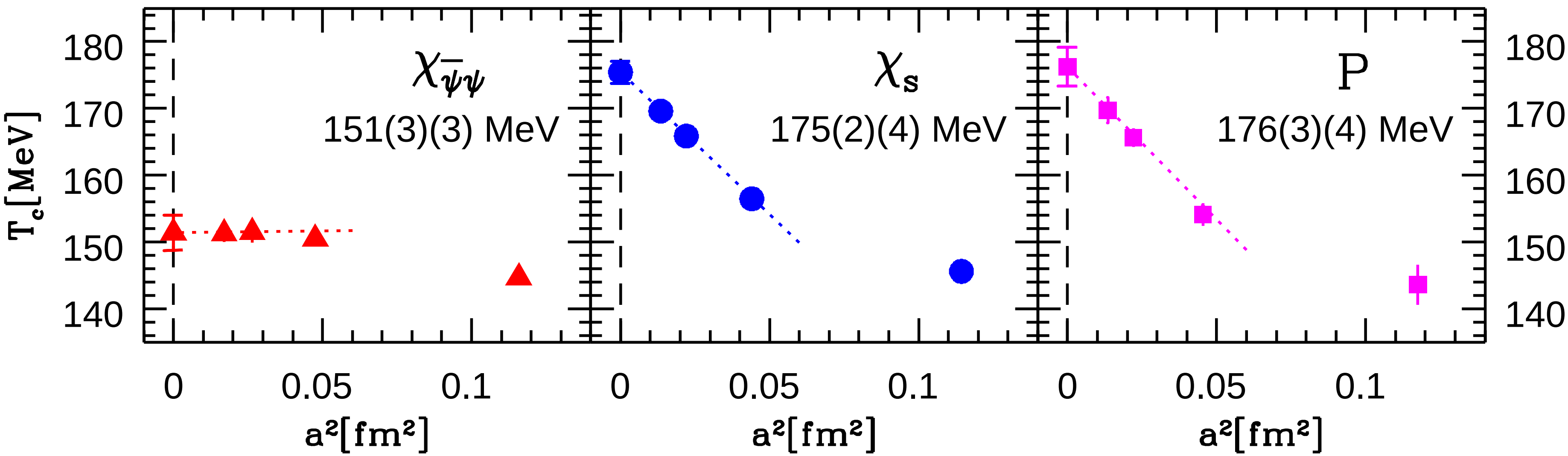
Transition temperatures

- RBC-Bielefeld (p4fat3 (p4)) vs. MILC (asqtad (Naik)) and Wuppertal (stout (stand. staggered)) vs. DIK-collaboration (clover improved Wilson)



extrapolations to phys. point

- RBC-Bielefeld (p4fat3 (p4)) vs. Wuppertal (stout (stand. staggered))
- stout results for different observables no longer consistent with each other for $N_\tau = 8, 10$

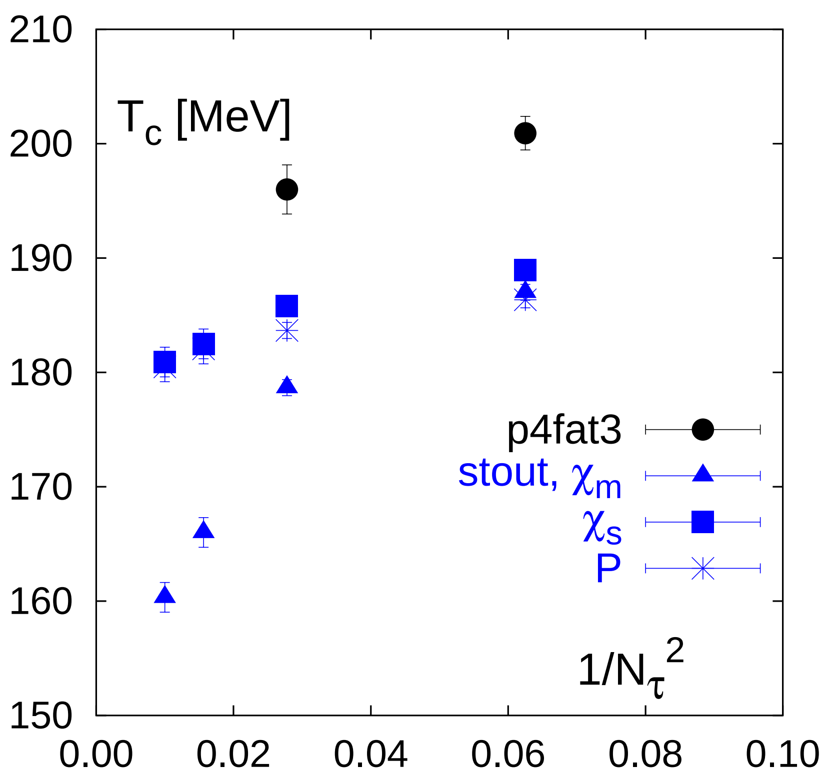


Y. Aoki et al, Phys. Lett. B643 (2006) 46

uses f_k to set the scale

extrapolations to phys. point

- RBC-Bielefeld (p4fat3 (p4)) vs. Wuppertal (stout (stand. staggered))
- stout results for different observables no longer consistent with each other for $N_\tau = 8, 10$
- results for $N_\tau = 4, 6$ differ by 15% but show similar cut-off dependence



overall scale set with

$r_0 = 0.469$ fm

Quark number susceptibility...
...and its susceptibility

- rapid change in quark/baryon/strangeness number susceptibility reflects change in mass of the carrier of these quantum numbers ⇔ DECONFINEMENT
- quark number susceptibility feels nearby singular point just like the energy density

scaling field: $t = \left|\frac{T-T_c}{T_c}\right| + A\left(\frac{\mu_q}{T_c}\right)^2 \quad , \quad \mu_{crit} = 0$

singular part: $f_s(T,\mu_q) = b^{-1} f_s(t b^{1/(2-\alpha)}) \sim t^{2-\alpha}$

Y. Hatta, T. Ikeda, PRD67 (2003) 014028

$$c_2 \equiv \chi_q \sim \frac{\partial^2 \ln \mathcal{Z}}{\partial \mu_q^2} \sim t^{1-\alpha} \quad , \quad c_4 \sim \frac{\partial^4 \ln \mathcal{Z}}{\partial \mu_q^4} \sim t^{-\alpha} \quad (\mu = 0)$$

$$\epsilon \sim \frac{\partial \ln \mathcal{Z}}{\partial T} \sim t^{1-\alpha} \quad , \quad C_V \sim \frac{\partial^2 \ln \mathcal{Z}}{\partial T^2} \sim t^{-\alpha} \quad (\mu = 0)$$

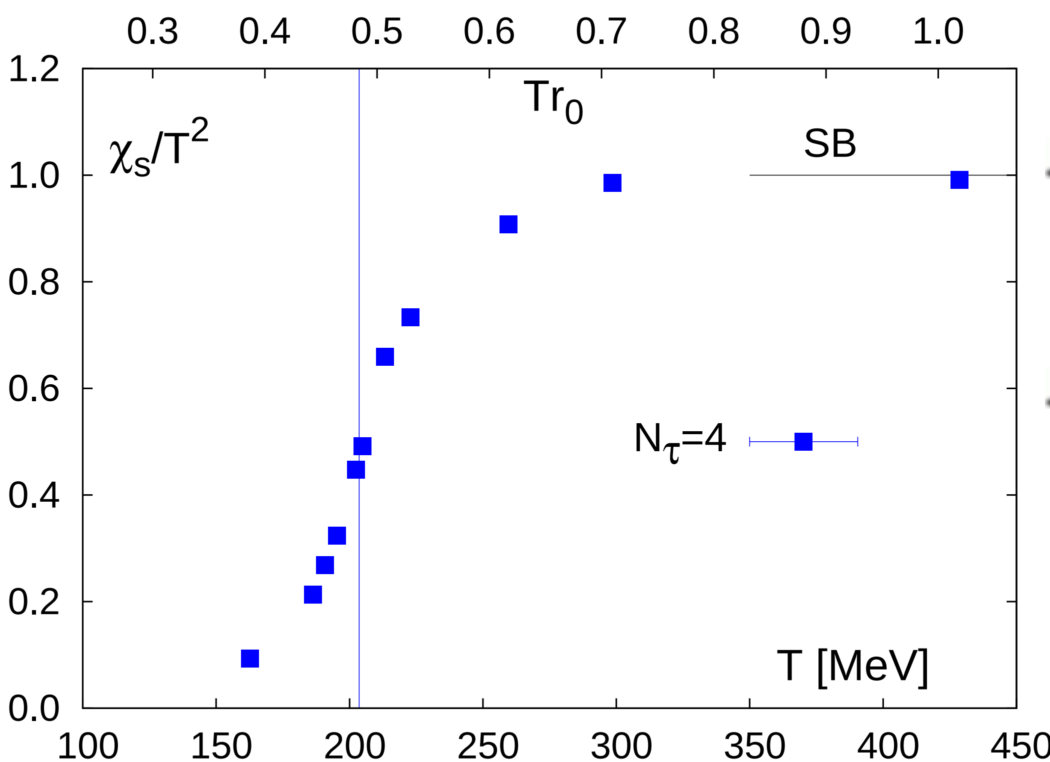
$\Rightarrow 2^{nd}$ derivative w.r.t μ_q ”looks like energy density”

$\Rightarrow 4^{th}$ derivative w.r.t μ_q ”looks like specific heat”

Light and Strange Susceptibilities

- quark number susceptibilities ⇔ coefficients of the leading order correction to the pressure

$$\left(\frac{p}{T^4}\right)_\mu - \left(\frac{p}{T^4}\right)_0 = \frac{1}{2}\frac{\chi_l}{T^2}\left(\frac{\mu_l}{T}\right)^2 + \frac{1}{2}\frac{\chi_s}{T^2}\left(\frac{\mu_s}{T}\right)^2 + \frac{\chi_{ls}}{T^2}\frac{\mu_l}{T}\frac{\mu_s}{T} + \mathcal{O}(\mu^4)$$



p4: RBC-Bielefeld, preliminary

strange quark number susceptibility:

- $T \to \infty$, ideal gas limit: $\chi_l/T^2, \chi_s/T^2 \quad \to \quad 1$

- lines here and in the following figures:

  $T_c r_0$ on $N_\tau = 4$

  determined for $m_q = 0.1 m_s$ in:

  M. Cheng et al (RBC-Bielefeld), PRD74, 054507 (2006)

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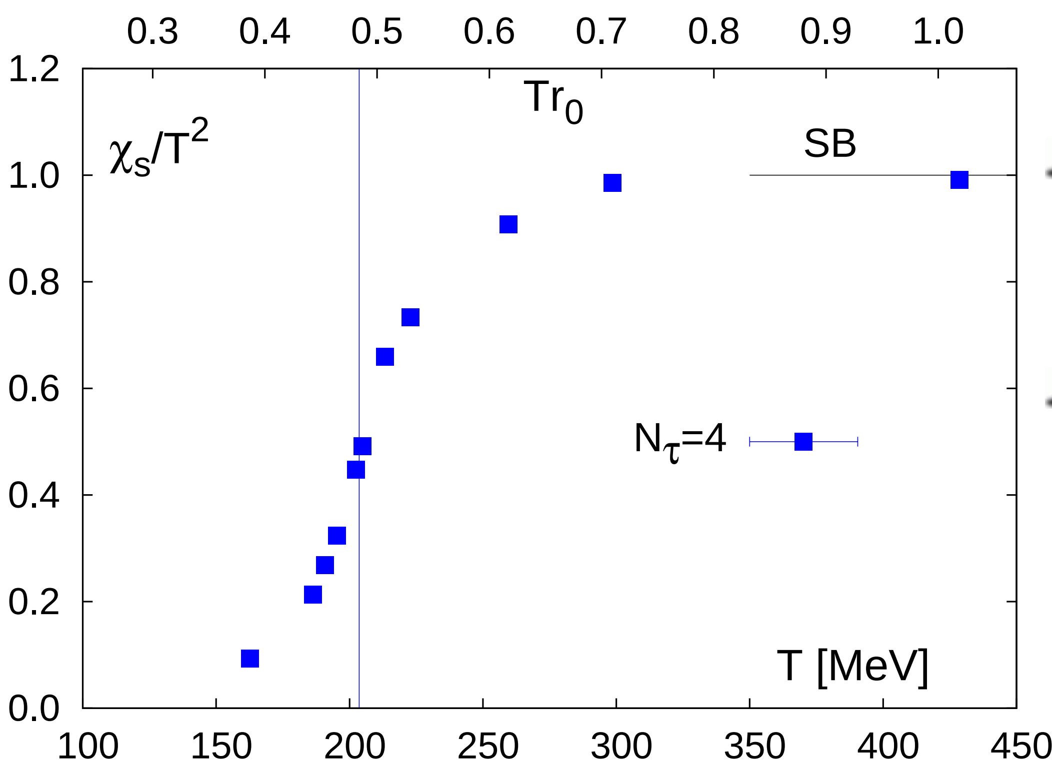

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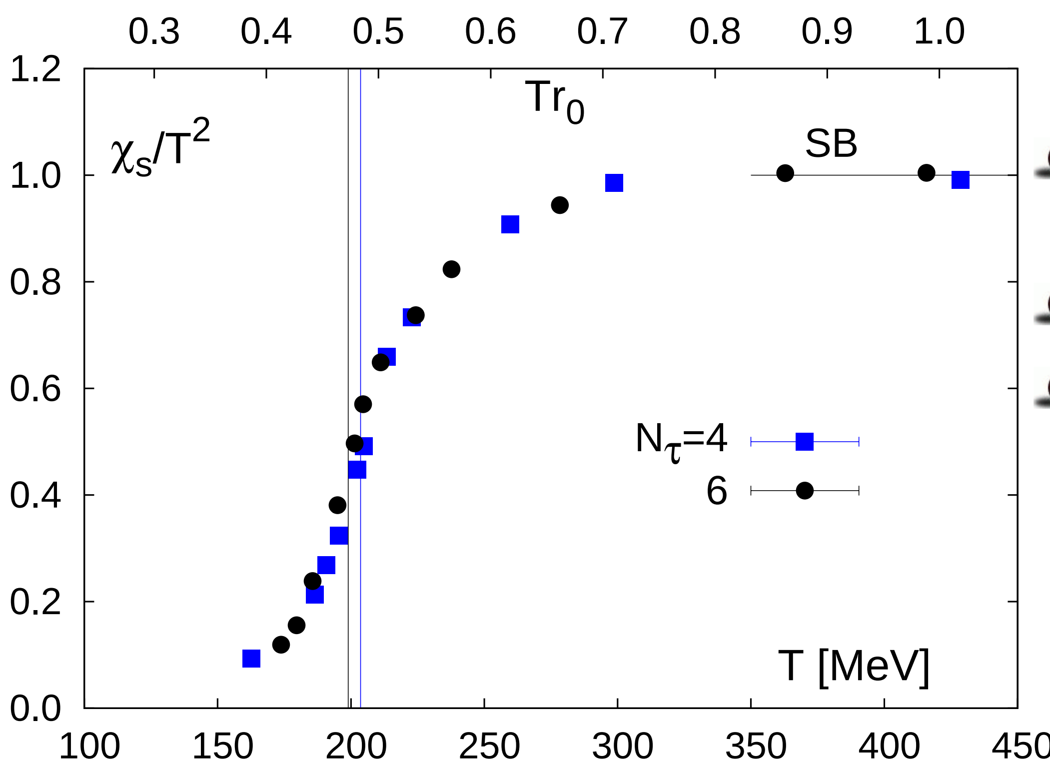

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strange quark number susceptibility:

- $T \rightarrow \infty$, ideal gas limit: $\chi_l/T^2, \chi_s/T^2 \quad \rightarrow \quad 1$
- small cut-off dependence
- lines here and in the following figures:

  $T_c r_0$ on $N_\tau = 4$ and 6 lattices determined for $m_q = 0.1 m_s$ in:

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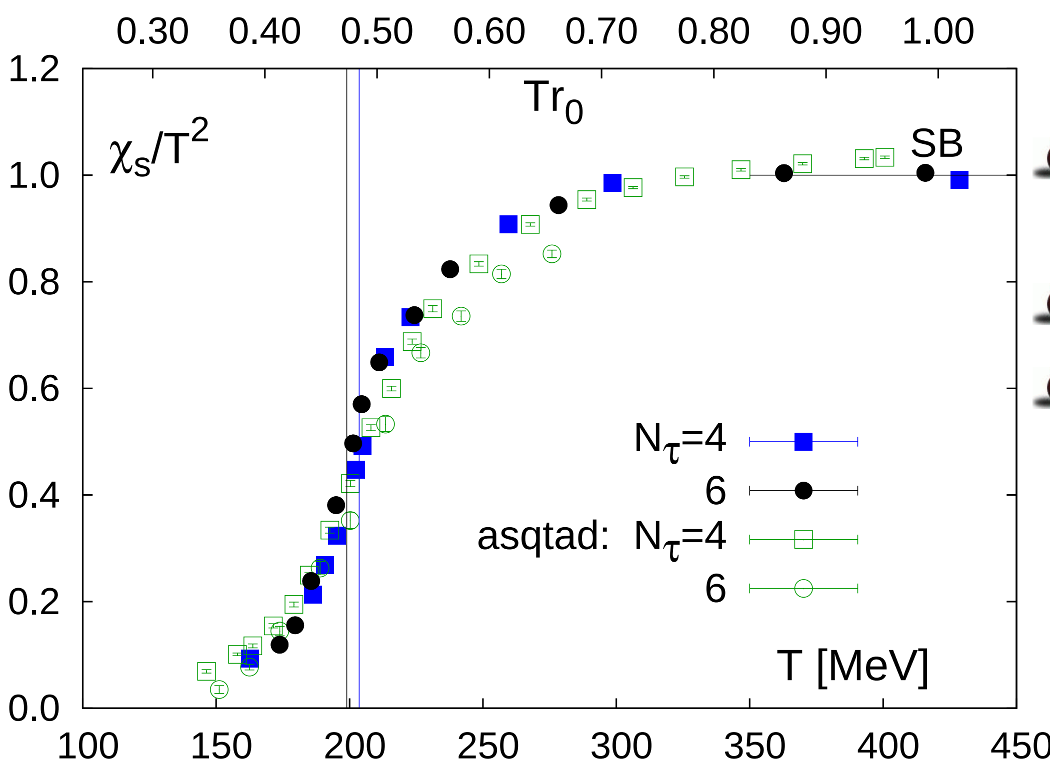


p4 versus asqtad

strange quark number susceptibility:

- $T \to \infty$, ideal gas limit: χ_l/T^2, $\chi_s/T^2 \quad \to \quad 1$
- small cut-off dependence
- good agreement with $\mathcal{O}(a^2)$ improved, asqtad fermion calculations

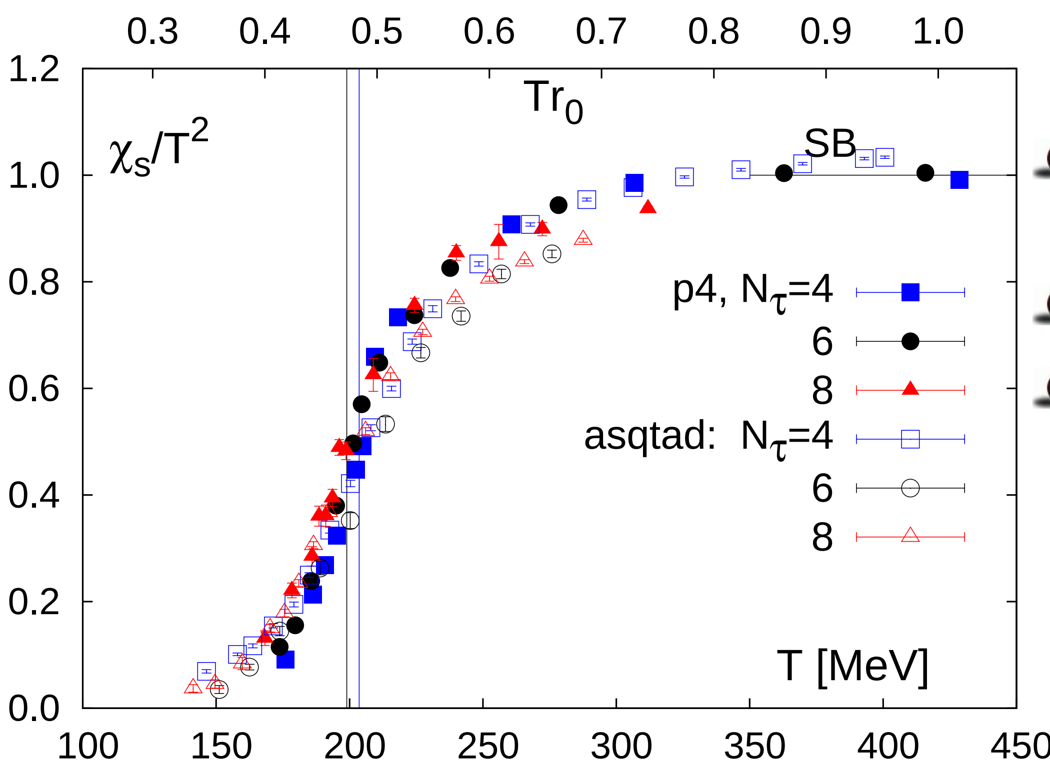
asqtad on $12^3 \times 4,\ 6$: C. Bernard et al (MILC), PRD71, 034504 (2005)

p4, $\mathcal{O}(a^2)$ improved RBC-Bielefeld, preliminary

Light and Strange Susceptibilities

- hotQCD, preliminary results for $32^3 \times 8$, $m_q = 0.1 m_s$

  good agreement between p4 and asqtad persists on finer lattices;
  small shifts in the transition temperature (inflection points)



p4 versus asqtad
$N_\tau = 8$: hotQCD, preliminary

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asqtad:
C. Bernard et al (MILC), PRD71, 034504 (2005)

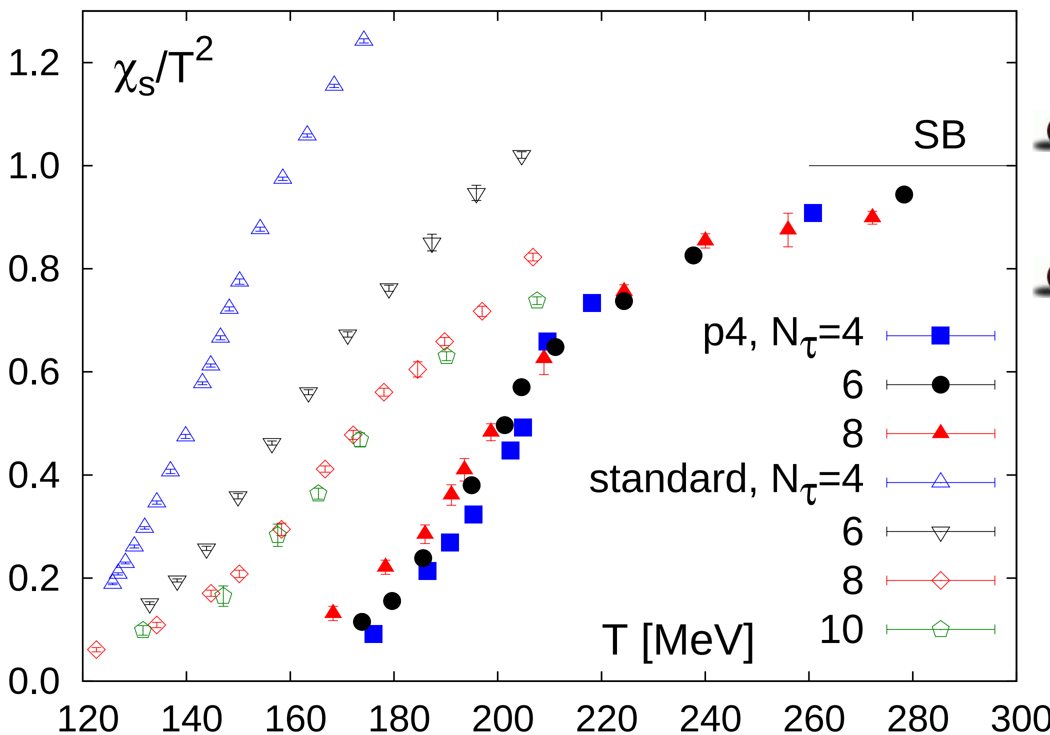
p4, $\mathcal{O}(a^2)$ improved
RBC-Bielefeld, preliminary

DECONFINEMENT:

Light and Strange Susceptibilities

1-link, stout, physical quark masses;
T-scale from f_K, but $f_K r_0$ consistent with asqtad value for r_0 in the continuum limit

p4fat3, $m_q = 0.1 m_s$, i.e. $m_\pi \simeq 220$ MeV;
T-scale from r_0 using the asqtad r_0 deduced from 'gold plated observables'



p4fat3 versus 1-link, stout

strange quark number susceptibility:

- $T \rightarrow \infty$, ideal gas limit:
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- similar cut-off dependence as pressure $\Rightarrow$ strong cut-off dependence in simulations with not $\mathcal{O}(a^2)$ improved actions

1-link, stout
Y. Aoki et al., PLB643, 46 (2006)

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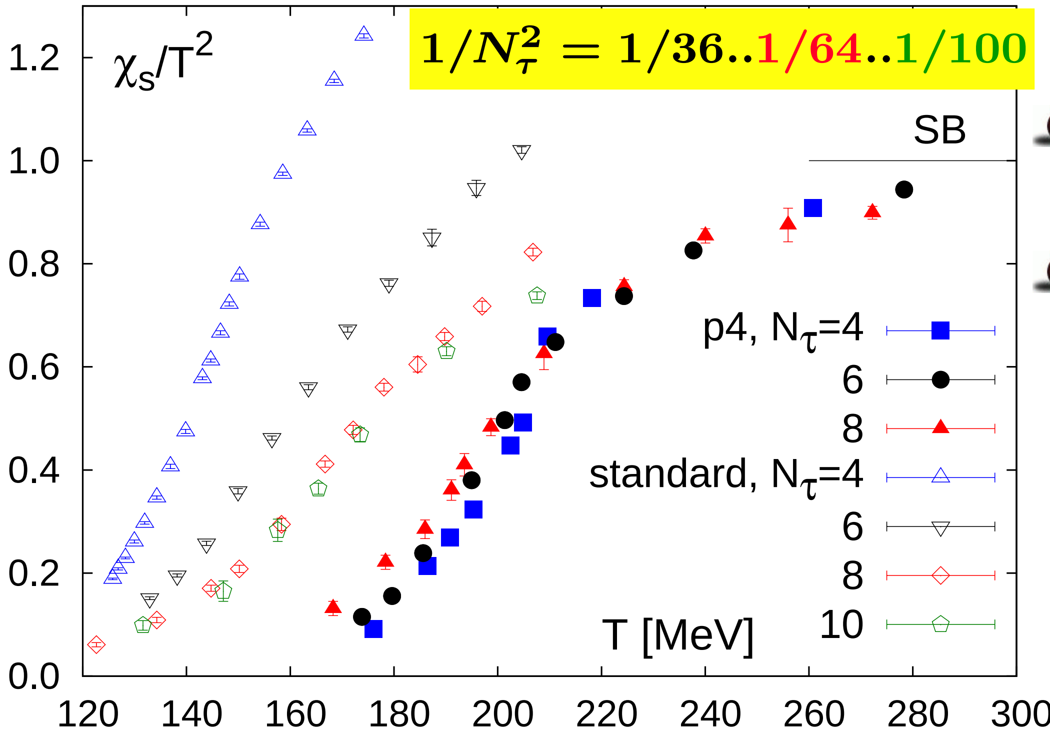
T-scale from r_0 using the asqtad r_0 deduced from 'gold plated observables'

expect still a shift of T-scale ~ 5 MeV for physical quark masses



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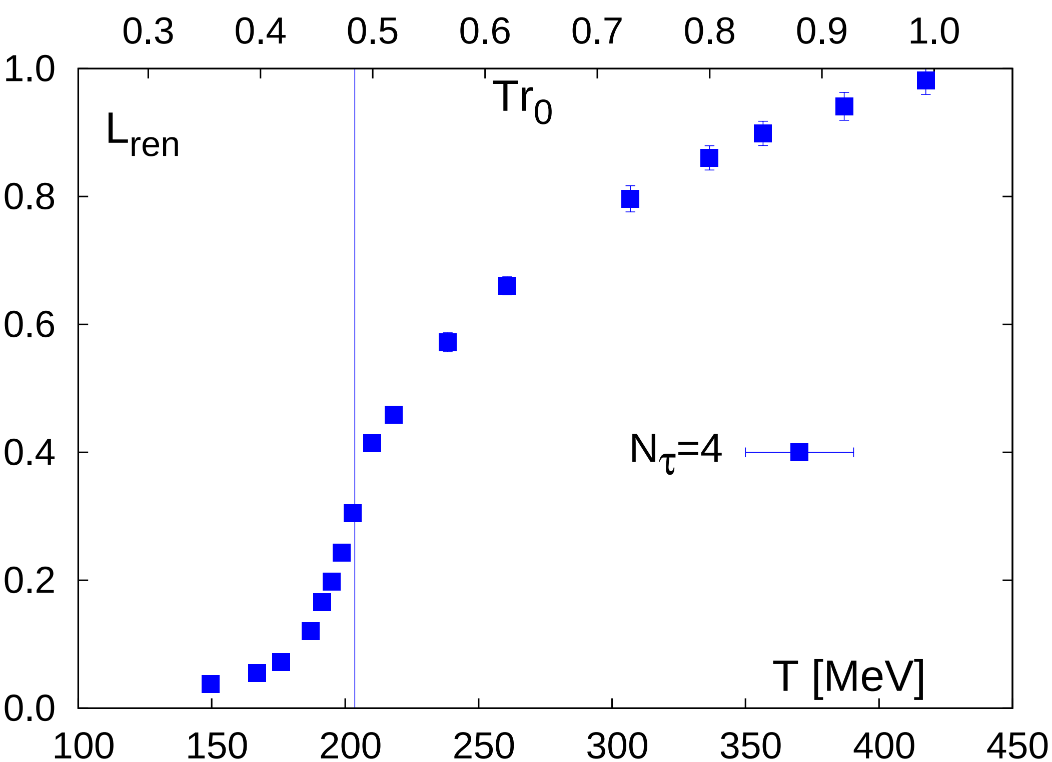
RBC-Bielefeld, preliminary
$N_\tau = 8$: hotQCD, preliminary

Renormalized Polyakov loop

- Polyakov loop expectation value $\langle L \rangle = \exp(-F_q(T)/T)$; needs renormalization of divergent quark self-energies:

$$L_{ren}(T) = Z(\beta)^{N_\tau} \langle L \rangle (T)$$



p4: RBC-Bielefeld, preliminary

used $T = 0$ potential to determine $Z(\beta)$ for each $T > 0$ parameter set

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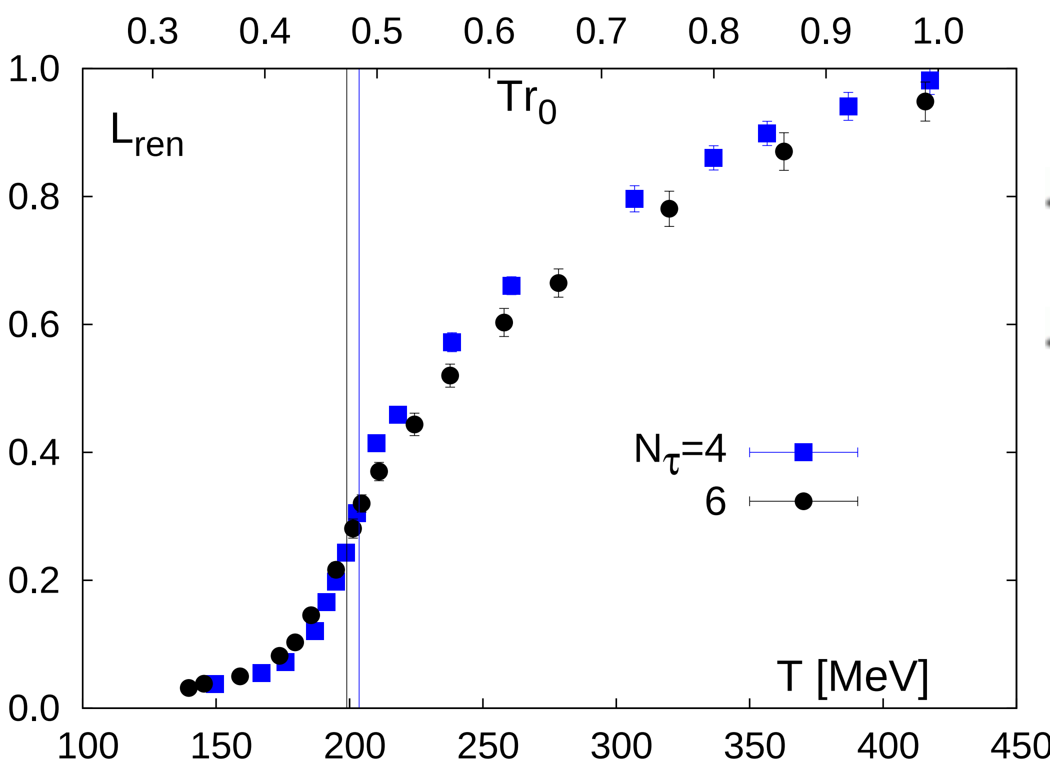

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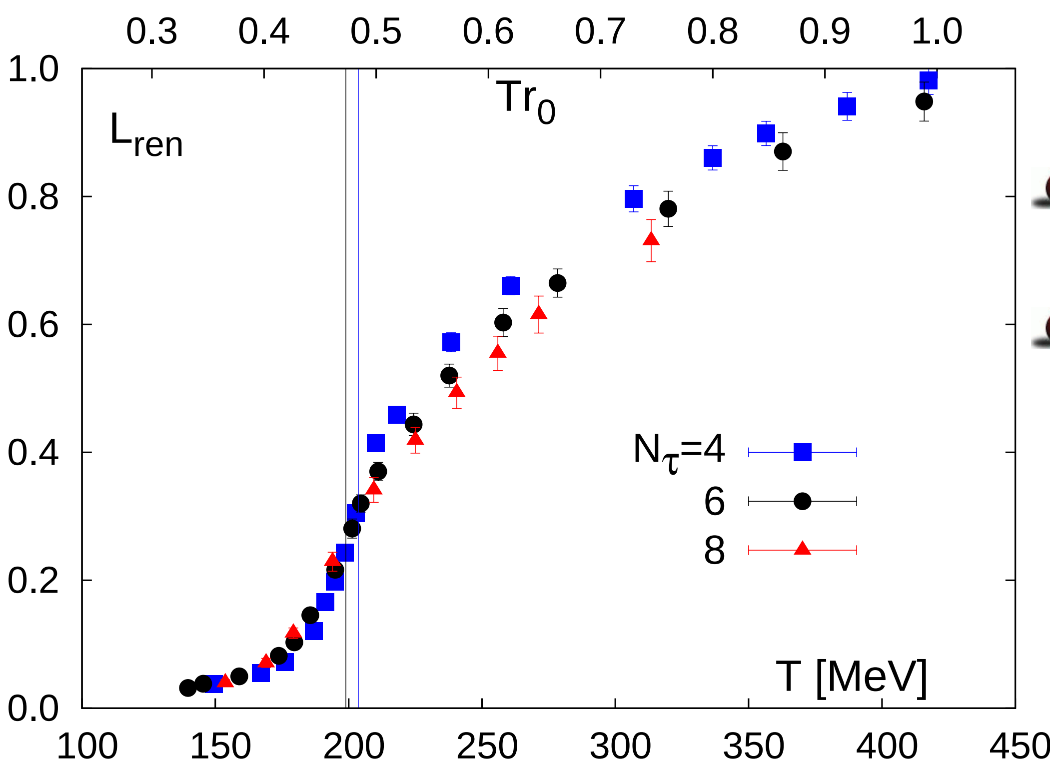

p4: RBC-Bielefeld, preliminary
hotQCD, preliminary

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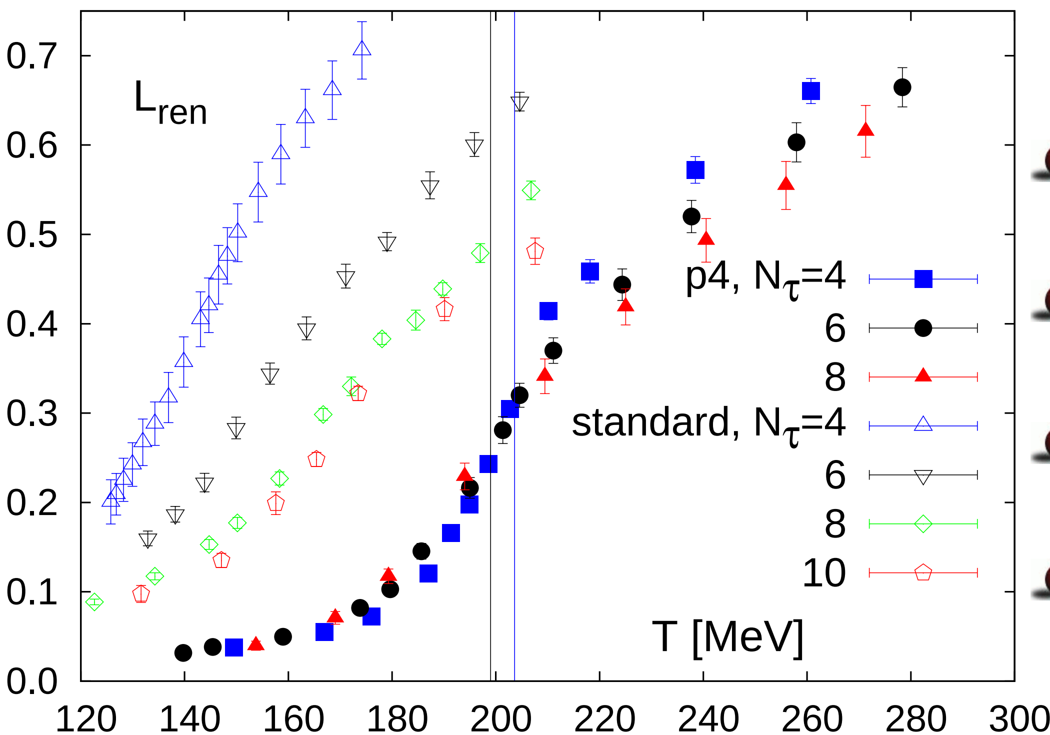
expect still a shift of T-scale ~ 5 MeV for physical quark masses



p4 versus standard

used $T = 0$ potential to determine $Z(\beta)$ for each $T > 0$ parameter set

- good scaling behavior of the renormalized Polyakov loop
- no significant cut-off dependence; confirms $SU(3)$ experience
- standard action L_{ren} rescaled with 1/5 (different renormalization scheme)
- quite different from findings with non $\mathcal{O}(a^2)$ improved actions; Y. Aoki et al., PLB643, 46 (2006)

EoS with $\mathcal{O}(a^2)$ improved SF

Goal: QCD thermodynamics with realistic quark masses in (2+1)-f QCD and controlled extrapolation to the continuum limit;

$\Rightarrow$ T_c, EoS,.. for $\mu_q \geq 0$

RBC-Bielefeld collaboration

- use an improved staggered fermion action that removes $\mathcal{O}(a^2)$ errors in bulk thermodynamic quantities and reduces flavor symmetry breaking inherent to the staggered formulation

  RBC-Bielefeld choice: p4-action + 3-link smearing (p4fat3)
  MILC: Naik-action + (3,5,7)-link smearing (asqtad)

  C. Bernard et al., PRD75, 094505 (2007)

- use RHMC algorithm to remove 'step-size errors'

- perform detailed $T = 0$ study of vacuum subtractions and scale setting for ALL $T > 0$ parameter sets

Calculating the EoS on lines of constant physics (LCP)

- The pressure

$$\frac{p}{T^4}\Big|_{\beta_0}^{\beta} = N_\tau^4 \int_{\beta_0}^{\beta} d\beta' \Big[\frac{1}{N_\sigma^3 N_t}(\langle S_g\rangle_0 - \langle S_g\rangle_T)$$

$$-\left(2(\langle\bar\psi\psi\rangle_{l0} - \langle\bar\psi\psi\rangle_{lT}) + \frac{\hat m_s}{\hat m_l}(\langle\bar\psi\psi\rangle_{s0} - \langle\bar\psi\psi\rangle_{sT})\right)\left(\frac{\partial \hat m_l}{\partial\beta'}\right)_{\hat m_s/\hat m_l}$$

$$-\hat m_l\,(\langle\bar\psi\psi\rangle_{s0} - \langle\bar\psi\psi\rangle_{sT})\left(\frac{\partial \hat m_s/\hat m_l}{\partial\beta'}\right)_{\hat m_l}\Big]$$

- The interaction measure for $N_f = 2+1$ $\Leftrightarrow$ Trace Anomaly

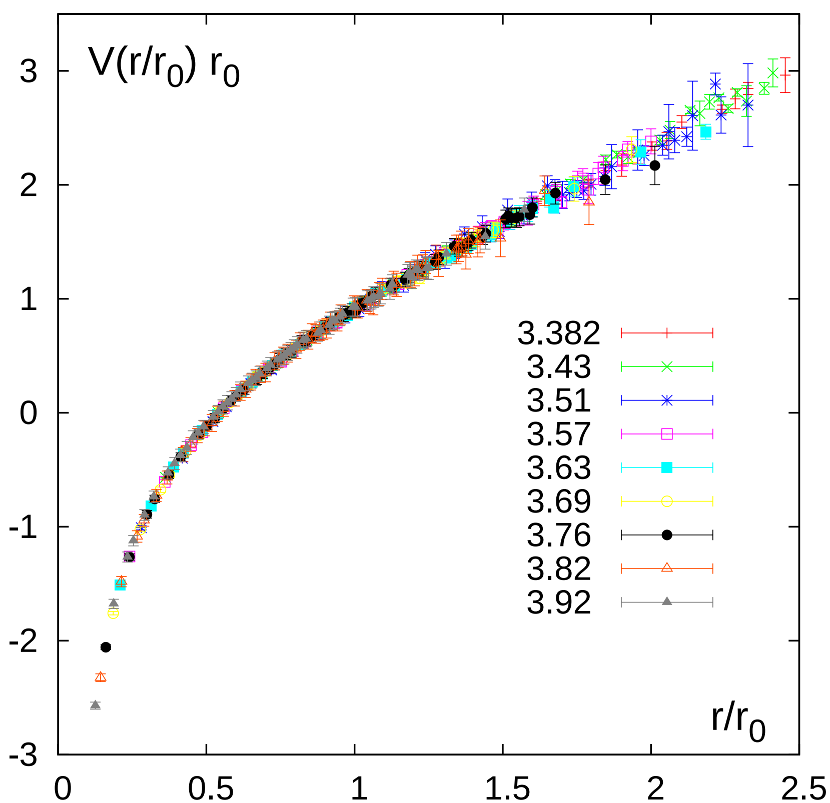
$$\frac{\epsilon-3p}{T^4} = T\frac{\mathrm{d}}{\mathrm{d}T}\left(\frac{p}{T^4}\right) = \left(a\frac{\mathrm{d}\beta}{\mathrm{d}a}\right)_{LCP}\frac{\partial p/T^4}{\partial\beta}$$

$$= \left(\frac{\epsilon-3p}{T^4}\right)_{gluon} + \left(\frac{\epsilon-3p}{T^4}\right)_{fermion} + \left(\frac{\epsilon-3p}{T^4}\right)_{\hat m_s/\hat m_l}$$

$T = 0$ scale setting using the heavy quark potential

use r_0 or string tension to set the scale for $T_c = 1/N_\tau a(\beta_c)$

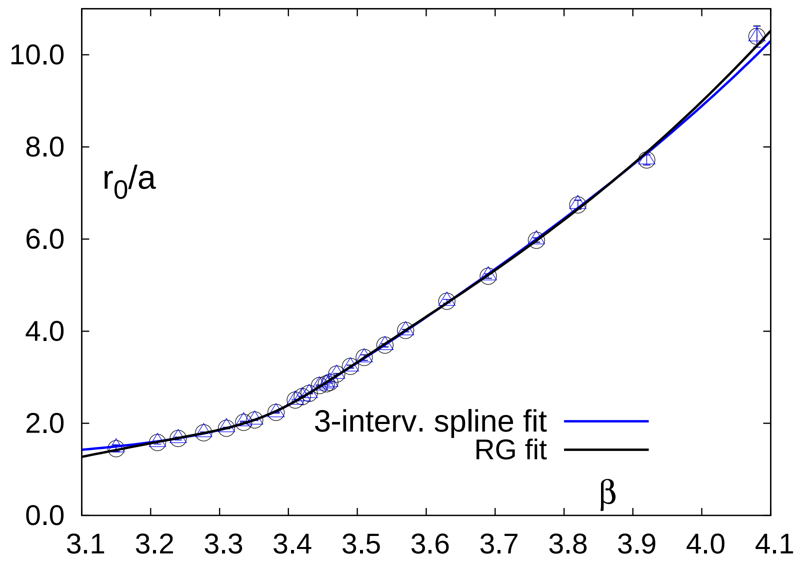
$$V(r) = -\frac{\alpha}{r} + \sigma r \quad , \quad r^2 \frac{\mathrm{d}V(r)}{\mathrm{d}r}\Big|_{r=r_0} = 1.65$$

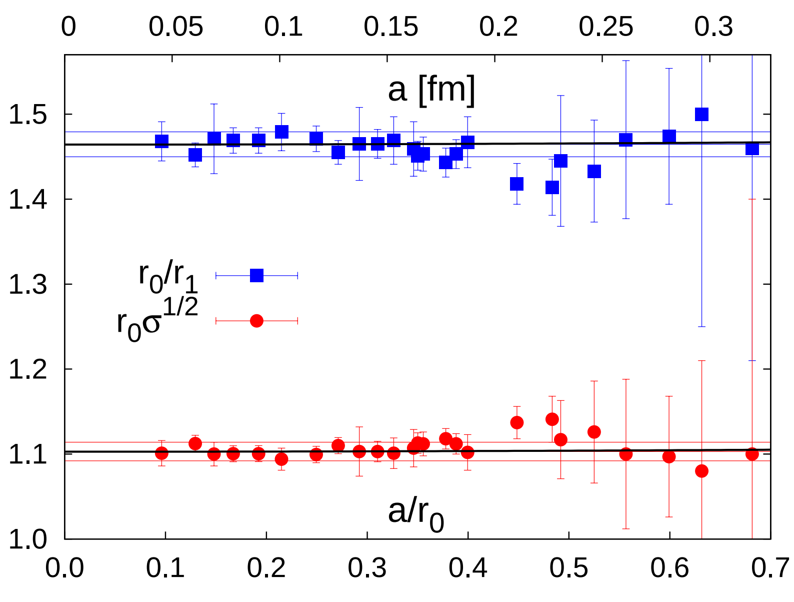


no significant cut-off dependence when cut-off varies by a factor 5

i.e. from the transition region on $N_\tau = 4$ lattices ($a \simeq 0.25$ fm) to that on $N_\tau = 20$ lattices ($a \simeq 0.05$ fm) !!

$T = 0$ scale setting using the heavy quark potential





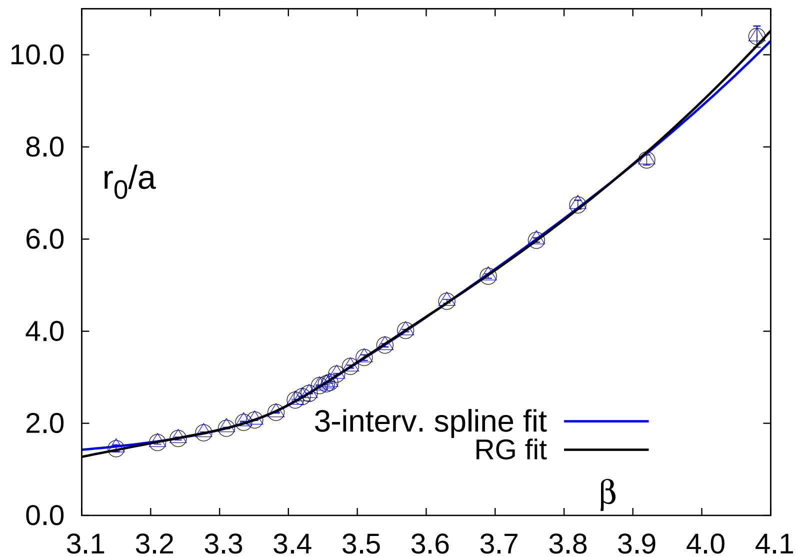
use r_0 to set the scale
for $T_c = 1/N_\tau a(\beta_c)$:

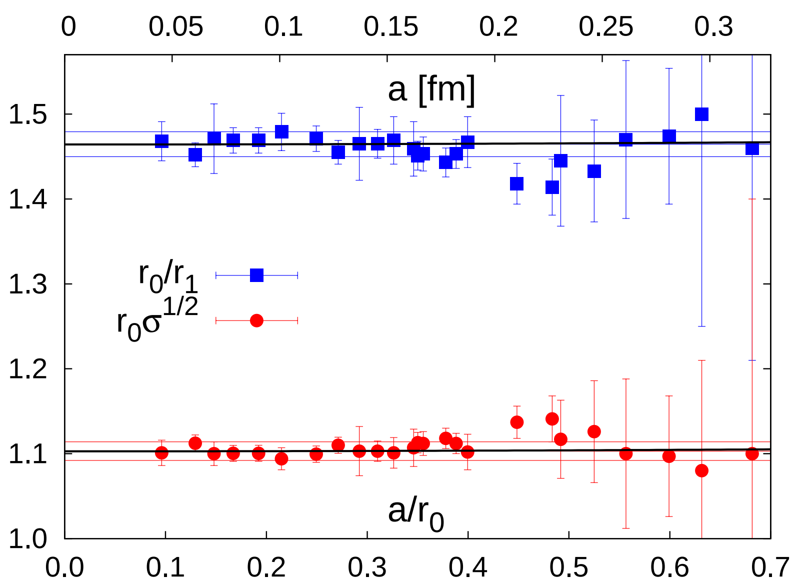
good control over r_0/a
$\Rightarrow \; T r_0 \equiv (r_0/a)/N_\tau$

r_0/r_1 and $r_0\sqrt{\sigma}$ vary by
less than 2% for $a \lesssim 0.2$ fm

no hint for large
$\mathcal{O}(a^2)$ corrections

$T = 0$ scale setting using the heavy quark potential





use r_0 to set the scale for $T_c = 1/N_\tau a(\beta_c)$:

good control over r_0/a
$\Rightarrow \; Tr_0 \equiv (r_0/a)/N_\tau$

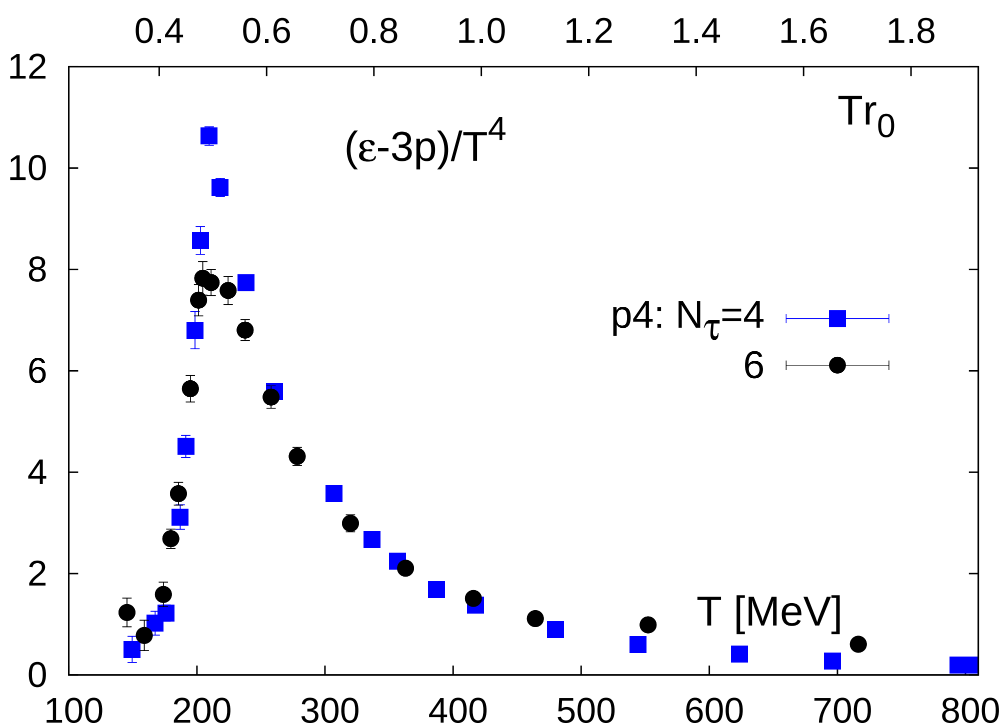
we use $r_0 = 0.469(7)$ fm determined from quarkonium spectroscopy
A. Gray et al, Phys. Rev. D72 (2005) 094507

r_0/r_1 and $r_0\sqrt{\sigma}$ vary by less than 2% for $a \lesssim 0.2$ fm

no hint for large $\mathcal{O}(a^2)$ corrections

$(\epsilon - 3p)/T^4$ on LCP

- overall good agreement between $N_\tau = 4$ and 6
- $N_\tau = 4$ data in peak region and below are sensitive to non-universal features of the β-functions



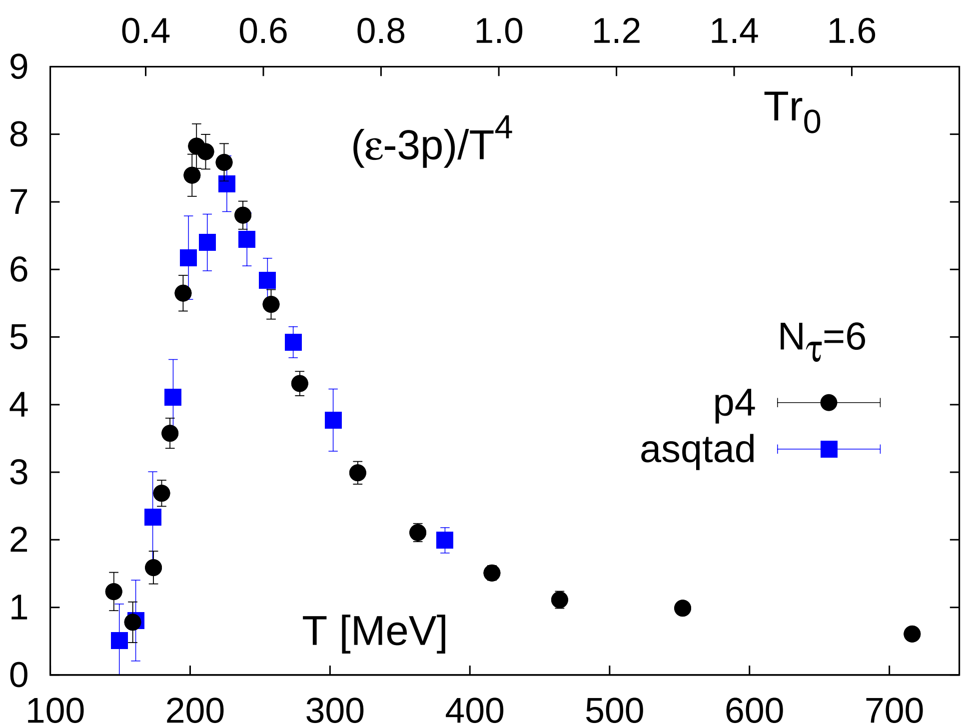
- $16^3 4$ and $24^3 6$ lattices
- $T = 0$ subtraction for each T-value
- statistical errors within symbol size

Note:
T-scale from $T = 0$ potential is an absolute scale, *i.e.* not dependent on T_c determination

RBC-Bielefeld, preliminary

$(\epsilon - 3p)/T^4$ on LCP

- overall good agreement between $N_\tau = 4$ and 6
- $N_\tau = 4$ data in peak region and below are sensitive to non-universal features of the β-functions
- $N_\tau = 6$ data in good agreement with asqtad simulations;
  C. Bernard et al. (MILC), PRD75, 094505 (2007)



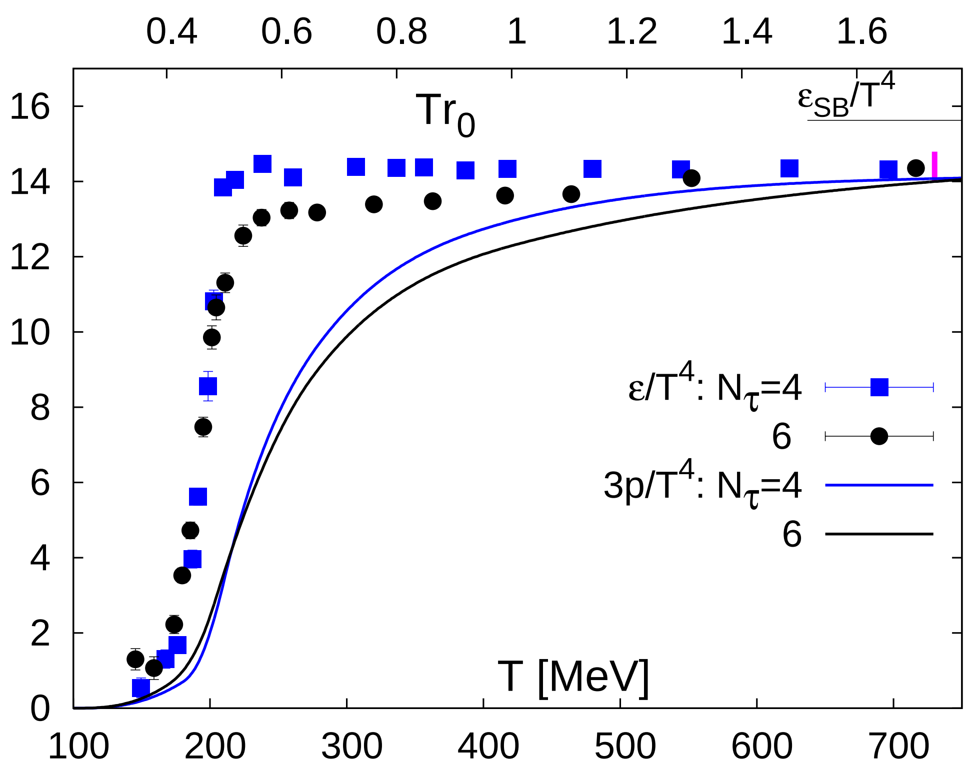
- $16^3 4$ and $24^3 6$ lattices
- $T = 0$ subtraction for each T-value
- statistical errors within symbol size

Note:
T-scale from $T = 0$ potential is an absolute scale, *i.e.* not dependent on T_c determination and totaly independent for p4-action and asqtad calculations

RBC-Bielefeld, preliminary

Pressure, Energy and Entropy

- p/T^4 from integration over $(\epsilon - 3p)/T^5$;
  systematic error arises from starting the integration at $T_0 = 100$ MeV with $p(T_0) = 0$;
  use hadron resonance gas to estimate systematic error: $[p(T_0)/T_0^4]_{HRG} \simeq 0.265$



p4: RBC-Bielefeld, preliminary

Pressure, Energy and Entropy

- p/T^4 from integration over $(\epsilon - 3p)/T^5$;
  systematic error arises from starting the integration at $T_0 = 100$ MeV with $p(T_0) = 0$;
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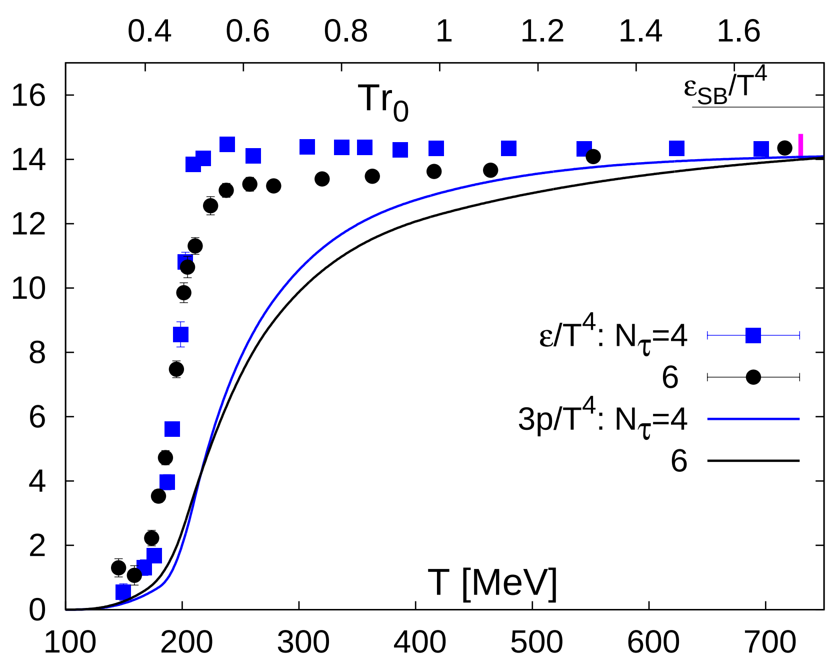
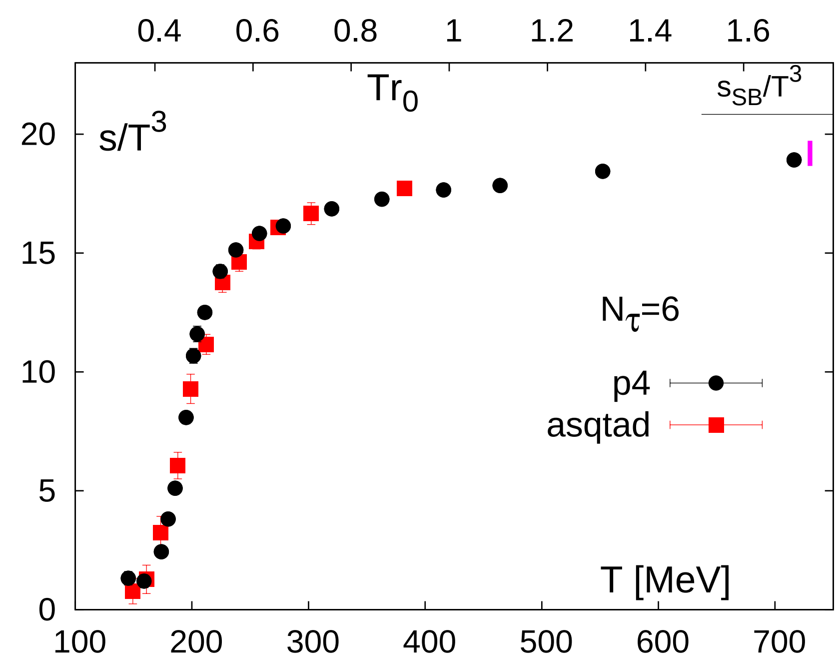




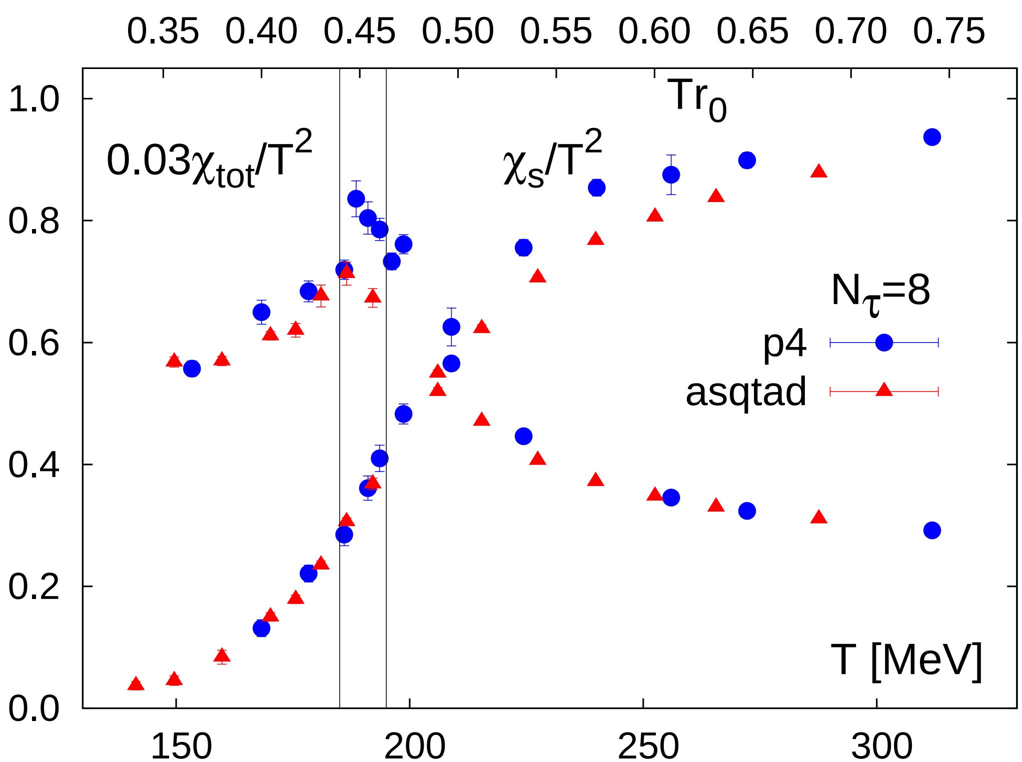
p4: RBC-Bielefeld, preliminary

asqtad: C. Bernard et al., PRD75, 094505 (2007)

entropy density: p4 vs. asqtad

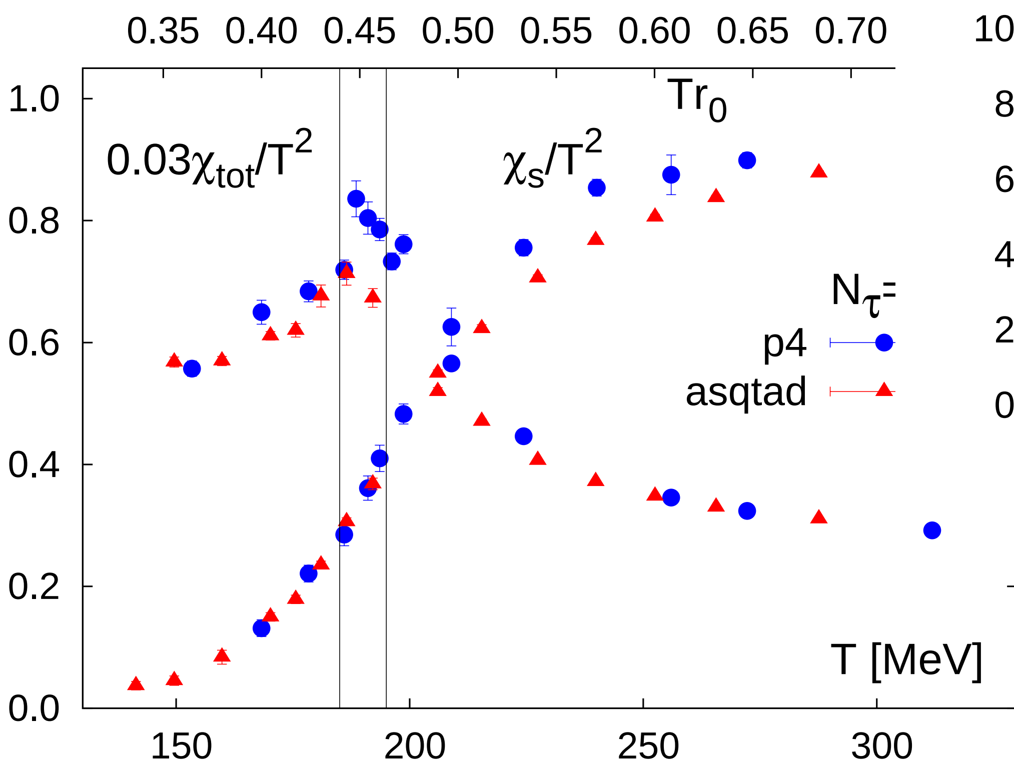
Deconfinement and χ-symmetry and bulk thermodynamics

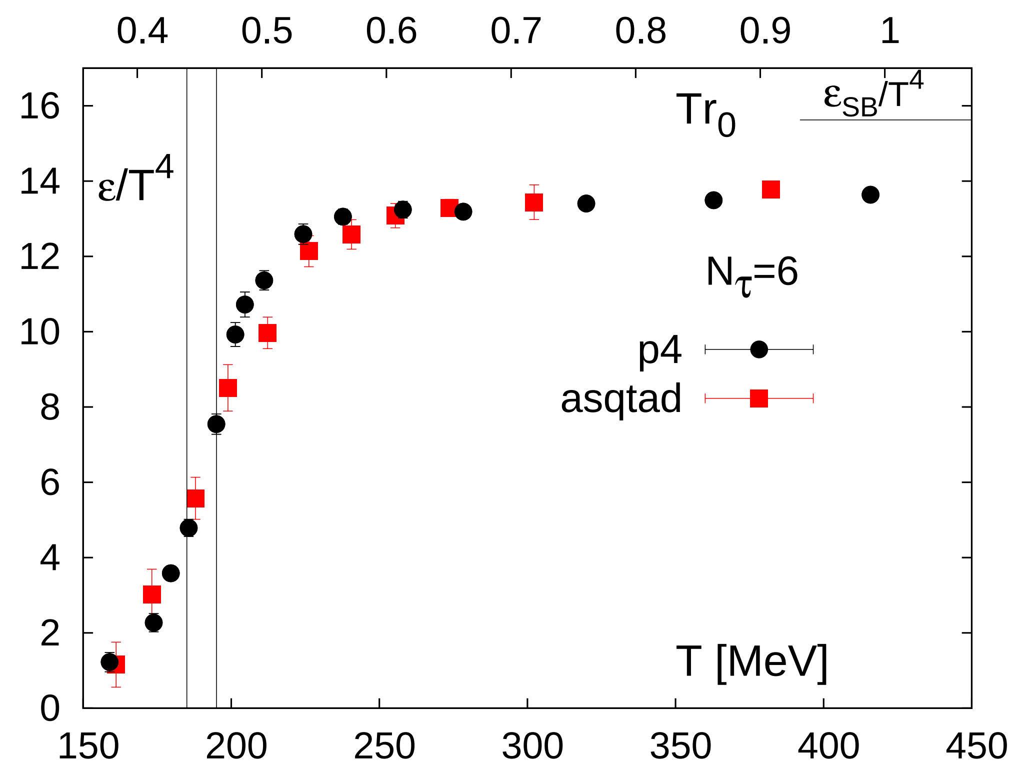
- most prominent features of bulk thermodynamics are related to deconfinement



Deconfinement and χ-symmetry and bulk thermodynamics

- most prominent features of bulk thermodynamics are related to deconfinement





Lattice EoS: energy density $\Leftrightarrow$ temperature
$\Longrightarrow$ conditions for heavy $q\bar{q}$ bound states

LGT: $T_c \simeq 190$ MeV

$T = T_c$: $\epsilon_c / T_c^4 \simeq 6 \;\Rightarrow\; \epsilon_c \simeq 1$ GeV/fm^3

$T \geq 1.5 T_c$: $\epsilon / T^4 \simeq (13 - 14)$

$T = 1.5 T_c$: $\epsilon \simeq 11$ GeV/fm^3

$T = 2.0 T_c$: $\epsilon \simeq 35$ GeV/fm^3

$\Downarrow$

observable consequences:

J/ψ suppression

RHIC

$R_{Au} \simeq 7$ fm;

$\tau_0 \simeq 1$ fm

$\langle E_T \rangle \simeq 1$ GeV

$dN/dy \simeq 1000$

$\Downarrow$

$\epsilon_{Bj} \simeq 7$ GeV/fm^3

maybe: $\tau_0 \simeq 0.5$ fm

$\Downarrow$

$\epsilon_{Bj} \simeq 14$ GeV/fm^3

Lattice EoS: energy density $\Leftrightarrow$ temperature

LGT: $T_c \simeq 190$ MeV - 170 MeV - 150 MeV

$T = T_c$: $\epsilon_c/T_c^4 \simeq 6 \;\Rightarrow\; \epsilon_c \simeq 1$ GeV/fm^3 - 0.64 GeV/fm^3 - 0.39 GeV/fm^3

let's assume: $\epsilon_c(T_\chi) \simeq 0.5\epsilon_c(T_{dec})$

$$\Rightarrow \quad \epsilon_c/T_\chi^4 \simeq 0.2 \text{ GeV/fm}^3$$

Conclusions

- $\mathcal{O}(a^2)$ improved actions drastically reduce cut-off effects
  - p4 and asqtad actions lead to consistent thermodynamics on lattices of temporal extent $N_\tau = 6$, although the handling of flavor symmetry breaking (fat-links) and $\mathcal{O}(a^2 g^2)$ corrections as well as cut-off effects in the free limit are quite different
- deconfinement and chiral symmetry restoration happen at roughly the same temperature that also characterizes the crossover region seen in bulk thermodynamics
- T_c needs to be confirmed on larger lattices

Extreme QCD 2007

This was an EXTREMEly interesting meeting

in an EXTREMEly pleasant sourounding

I guess we all are EXTREMEly thankful to Maria for

arranging this years xQCD meeting