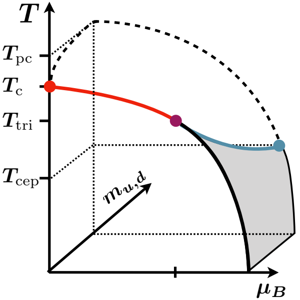


[F. Karsch, arXiv:1905.03936]

Screening masses towards chiral limit

Simon Dentinger

In cooperation with F. Karsch, O. Kaczmarek, A. Lahiri

July 30th, 2020

CRC-TR 211 Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

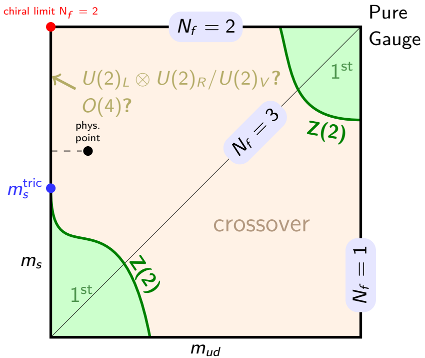
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Outline

Outline

Motivation

Scaling behavior of observables around critial point depends on universality class of critical point

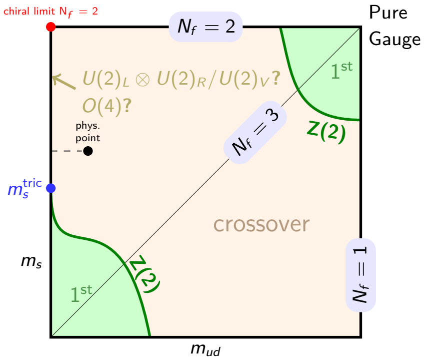


- 2^{nd} order in chiral limit
- $O(4)$ or $U_L(2) \otimes U_R(2)/U_V(2)$

Owe Philipsen, Christopher Pinke, Phys. Rev. D **93** 114507 (2016)

Motivation

Scaling behavior of observables around critial point depends on universality class of critical point



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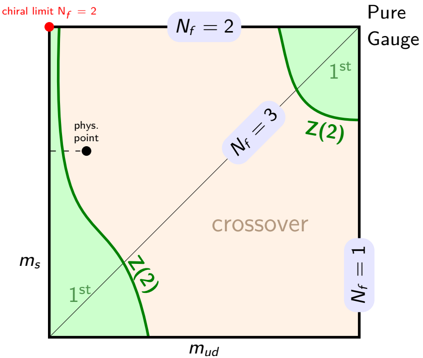


- 1^{st} order in chiral limit
- $Z(2)$

Owe Philipsen, Christopher Pinke, Phys. Rev. D **93** 114507 (2016)

Motivation

$U_A(1)$ distinguishes between $O(4)$ and different universality classes

chiral limit

$U_A(1)$ broken

$O(4)$

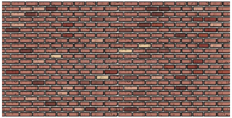
Motivation

$U_A(1)$ distinguishes between $O(4)$ and different universality classes

chiral limit

$U_A(1)$ broken

$U_A(1)$ effectively restored



$O(4)$

1st order

$U_L(2) \otimes U_R(2)/U_V(2)$

Outline

$U_A(1)$ and screening masses

S_{QCD} is invariant under $U_A(1)$ for $m_{u,d} = m_l = 0$, but

$$C = \langle X \rangle = \frac{1}{Z} \int \mathcal{D}[\psi, \bar{\psi}] \mathcal{D}[U] \exp(-S_{\mathsf{QCD}}[U, \psi, \bar{\psi}]) X[U, \psi, \bar{\psi}]$$

$\mathcal{D}[\psi, \bar{\psi}] = \mathcal{D}[\psi', \bar{\psi}'](1 - 2\mathrm{i}\varepsilon N_f Q_{\mathsf{top}} + \mathcal{O}(\varepsilon^2))$

$\rightarrow$ invariance depends on invariance of measure
$\rightarrow$ **anomaly of $U_A(1)$**

Gattringer, Lang: Quantum Chromodynamics on the Lattice

$U_A(1)$ and screening masses

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$\rightarrow$ **anomaly of $U_A(1)$**

e.g. $O_{\pi^+}(n_{\tau/s}) = \bar{d}(n_{\tau/s}) \gamma_5 u(n_{\tau/s}) \rightarrow$

$C_\pi(n) = \langle O_\pi(n) O_\pi^\dagger(0) \rangle = \sum_k \langle 0| O_\pi(0) |k\rangle \langle k| O_\pi^\dagger(0) |0\rangle \exp(-naE_k)$

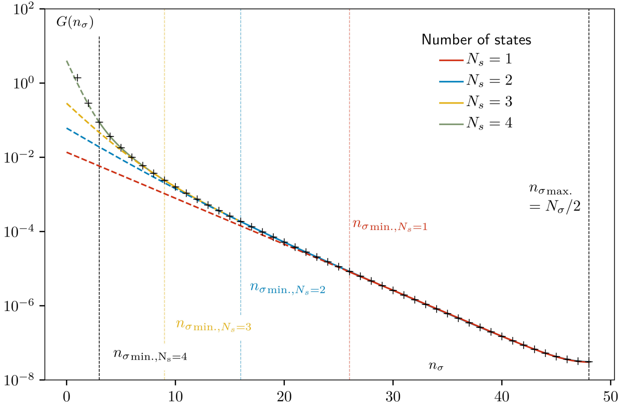
If $U_A(1)$ is effectively restored

- C_{a_0} and C_π degenerate

$\rightarrow$ corresponding masses also degenerate

Gattringer, Lang: Quantum Chromodynamics on the Lattice

Screening mass extraction



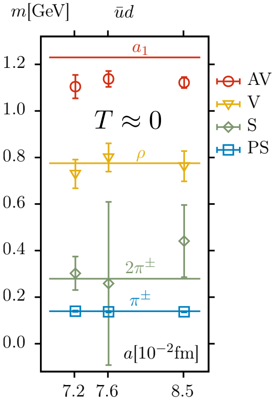
$$G(n_\sigma) = \sum_k A_k \cosh(a m_k (n_\sigma - N_\sigma/2))$$

Hauke Sandmeyer PhD thesis

Outline

Screening masses for physical masses

$U_A(1)$ effectively restored $\rightarrow m_{\text{scalar}} = m_{\text{pseudo-scalar}}$



- $T = 0$: $m_{\text{screen.}} = m_{\text{pole}}$
- physical mass $m_l/m_s = 1/27$

A. Bazavov, S. Dentinger et. al., Phys. Rev. D **100**, 094510 (2019)

Screening masses for physical masses

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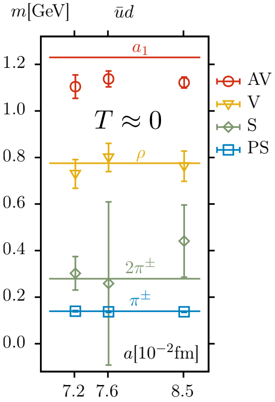

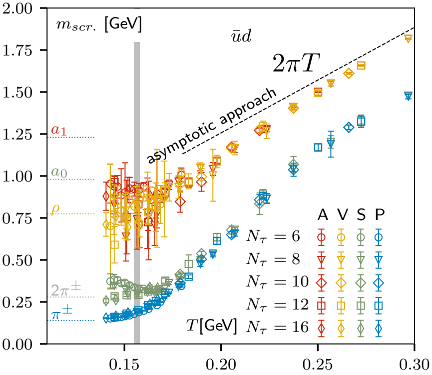

- $T = 0$: $m_{\text{screen.}} = m_{\text{pole}}$
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- AV-V degenerate at T_{pc}

A. Bazavov, S. Dentinger et. al., Phys. Rev. D **100**, 094510 (2019)

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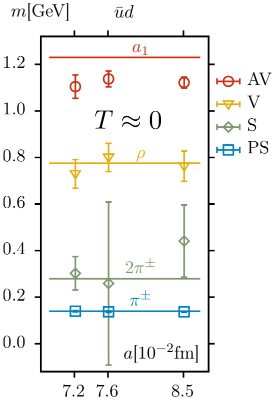
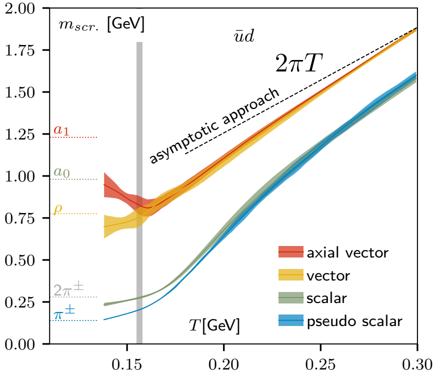




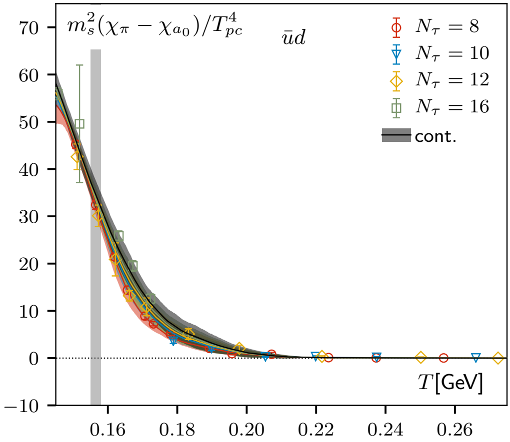
- $T = 0$: $m_{\text{screen.}} = m_{\text{pole}}$
- physical mass $m_l/m_s = 1/27$

- AV-V degenerate at T_{pc}
- S-PS degenerate at $\approx 1.3\ T_{\text{pc}} \rightarrow$ $U_A(1)$ effectively restored

A. Bazavov, S. Dentinger et. al., Phys. Rev. D **100**, 094510 (2019)

Susceptibilities for physical masses

Why? Susceptibilities independent of multiple state fits



$$\chi_\pi = \sum_{n=0}^{N_s-1} C_\pi(n)$$

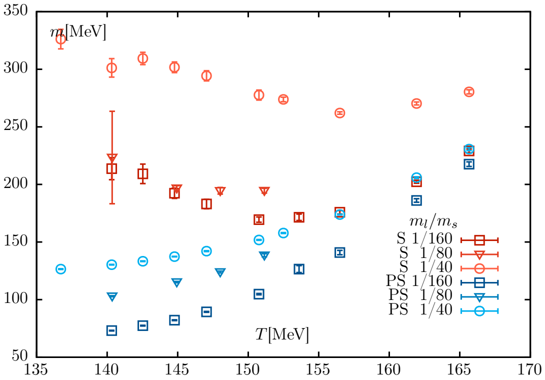
$$\chi_\delta = -\sum_{n=0}^{N_s-1} (-1)^n C_\delta$$

- $U_A(1)$ effectively restored $\rightarrow \chi_\pi = \chi_{a_0/\delta}$
- $U_A(1)$ effectively restored at $\approx 1.3\ T_{\rm pc}$

A. Bazavov, S. Dentinger et. al., Phys. Rev. D **100**, 094510 (2019)

Outline

Screening masses lower than physical quark masses



- first thermodynamic limit $N_s \to \infty$
- then continuum limit $N_\tau \to \infty$
- finally chiral limit $m_l \to 0$

Thermodynamic limit of screening masses

Thermodynamic limit for screening masses is

$$m_{N_s/N_\tau} = m_{N_s\to\infty/N_\tau}\left(1 + b_{N_\tau}\left(\frac{N_\tau}{N_s}\right)^c\right),$$

where $c = 3$ for $T = 0$, $c = 1$ for $T \to \infty$. Therefore $c \in [1, 3]$ for any T.

M.Fukugita, H.Mino et al., Phys. Lett. **B294**, 380 (1992)

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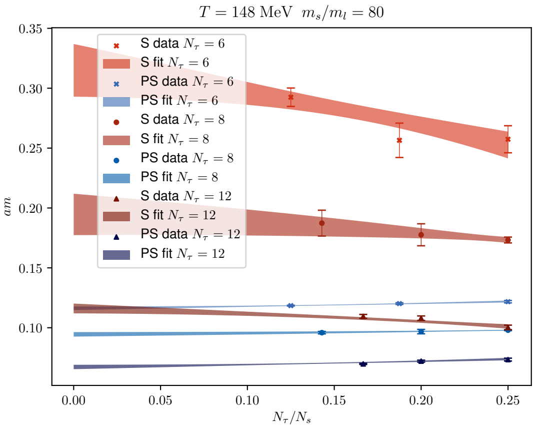
Assumptions:

- $m_{N_s\to\infty/N_\tau}$ and b_{N_τ} depends on N_τ, particle type (e.g. pion) and T
- c only depends on T

$\Rightarrow$ combined fit for pseudoscalar and scalar particle for different N_τ possible with shared parameter c

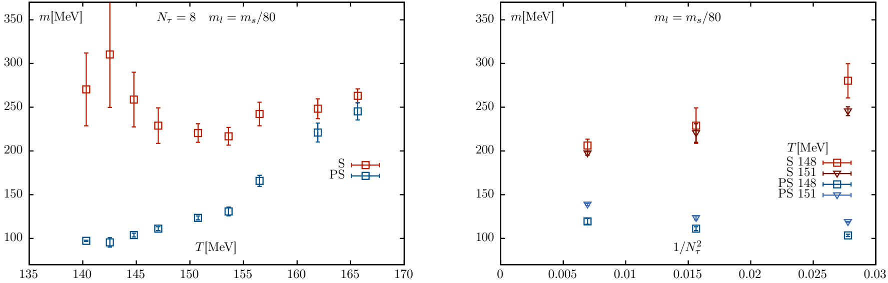
M.Fukugita, H.Mino et al., Phys. Lett. **B294**, 380 (1992)

Thermodynamic limit of screening masses



- $N_s \to \infty$ at fixed N_τ
- combined fit with shared c for $N_\tau = 6, 8, 12$ for the scalar and pseudoscalar mass
- fits dominated by small uncertainty for the pseudoscalar particle

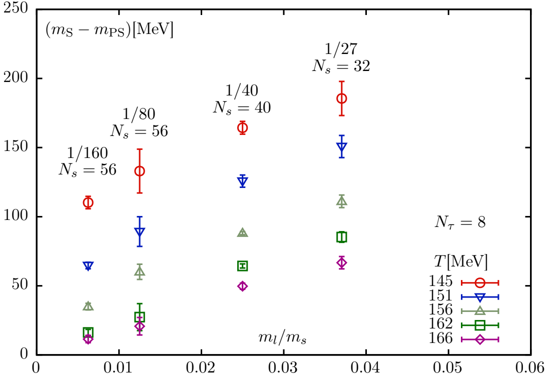
Results in thermodynamic limit of screening masses



- $N_s \to \infty$ extrapolated masses
- only for two T for all N_τ values
- continuum limit possible
- $1/N_\tau^2$ dependence expected

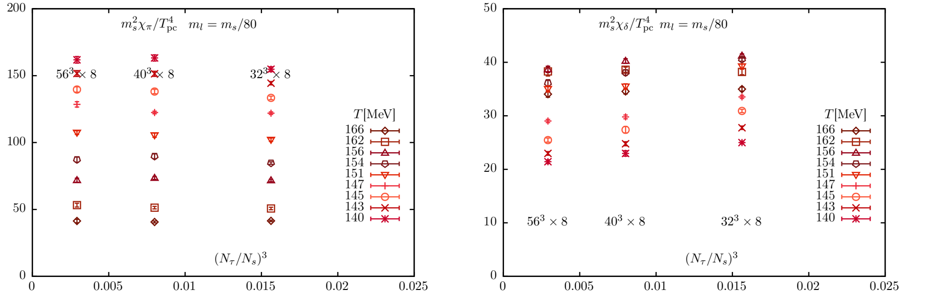
Screening masses in chiral limit

$U_A(1)$ effectively restored $\rightarrow m_{\text{scalar}} = m_{\text{pseudo-scalar}}$



- masses degenerate at high T
- degenerate at $T_c = 132^{+3}_{-6}$ MeV?

H.-T. Ding, P. Hegde et. al., Phys. Rev. Lett. **123**, 062002 (2019)

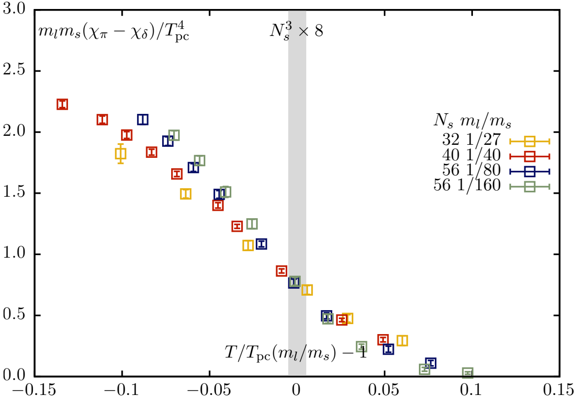


χ_π related to dimensionless order parameter of chiral condensate M.
Thermodynamic limit can be obtained using finite size scaling function (compare to talk of A. Lahiri).
Regular correction for χ_δ expected

$$\chi_\delta(N_s) = \chi_\delta(\infty) + g(N_\tau)\frac{1}{V} = \chi_\delta(\infty) + d(N_\tau)\frac{1}{N_s^3}.$$

H.-T. Ding, P. Hegde et. al., Phys. Rev. Lett. **123**, 062002 (2019)

Susceptibilities in chiral limit



$$\chi_\pi = \sum_{n=0}^{N_s-1} C_\pi(n)$$

$$\chi_\delta = -\sum_{n=0}^{N_s-1} (-1)^n C_\delta$$

- rescaled plot
- lower $m_l/m_s \to$ steeper
- $U_A(1)$ probably broken in chiral limit at T_c since $1/160$ close to 0

Outline

Periodic temporal boundary conditions

In infinite temperature limit states go towards $E = \sqrt{\Omega^2 + m_{tot}^2}$, with lowest Matsubara frequency Ω

- fermions have $\Omega = \pi T$

$\rightarrow$ for two fermions $E \approx 2\pi T$

- bosons have $\Omega = 0$

$\rightarrow$ $E = m_{tot}$

G. Boyd, Sourendu Gupta et al., Z. Phys. C **64**, 331-338 (1994)

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$\rightarrow$ $E = m_{tot}$

Switching the boundary conditions in the temporal direction from anti-periodic to periodic we change the nature of valence quarks from fermionic to bosonic states

- mesons are always bosons

$\rightarrow$ screening mass at low T unchanged

- around and above $T_{\rm pc}$ meson splits into quark states

$\rightarrow$ split in screening masses for anti-periodic and periodic temporal boundary conditions

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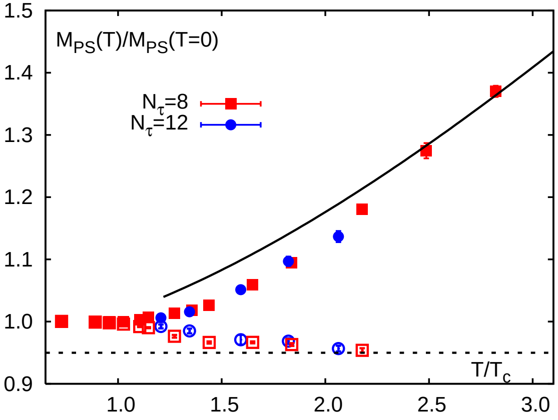
G. Boyd, Sourendu Gupta et al., Z. Phys. C **64**, 331-338 (1994)

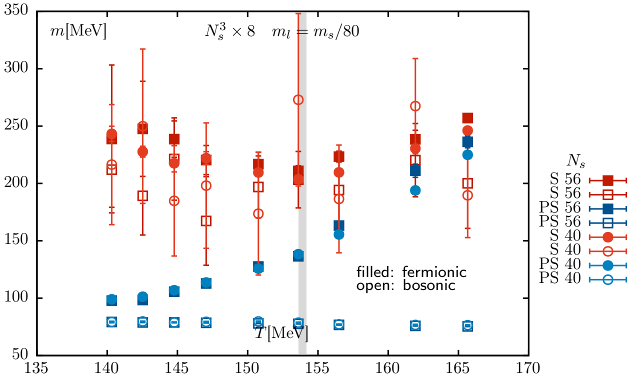
Periodic temporal boundary conditions



- charmonium
- filled (open) points: Fermionic (bosonic) quarks
- split around T_c

F. Karsch et al., Phys. Rev. D **85**, 114501 (2012)

Periodic temporal boundary conditions

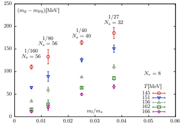


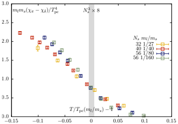
- $m_\pi = 80$ MeV
- periodic temporal BC: Bosons
- anti-periodic temporal BC: Fermions
- split before $T_{\rm pc}$

Outline

CRC-TR 211

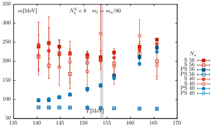
Summary & Outlook





Summary

- scaling behavior of observables around critial point depends on universality class of critical point
- $U_A(1)$ distinguishes between $O(4)$ and other universality classes
- $U_A(1)$ symmetry can be checked via screening meson correlators
- splitting of screening masses for periodic and anti-periodic temporal boundary condition around and above T_{pc}



Outlook

- limits have to be taken $\rightarrow$ continuum limit, chiral limit
- limits for susceptibilities
- splitting T periodic and anti-periodic temporal boundary condition
- compare with other methods $\rightarrow$ chiral condensate, topology

Appendix