Thermal modifications of mesons and restoration of broken symmetries from spatial correlation functions in HISQ

Yu Maezawa (YITP, Kyoto University)

in collaboration with

Frithjof Karsch (Universität Bielefeld, Brookhaven National Lab.)
Swagato Mukherjee (Brookhaven National Lab.)
Peter Petreczky (Brookhaven National Lab.)

LATTICE2015, Kobe, Japan, July 14--18

Introduction

Thermal fluctuation in QCD

Modifications of hadrons

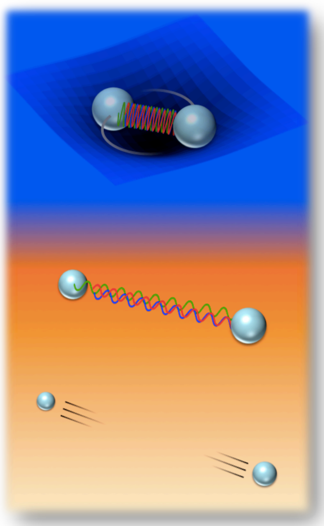
sequential melting pattern
of **quarkonium** and
open-flavor mesons
e.g. J/ψ suppression

Matsui and Satz (1986)

Restorations of broken symmetries

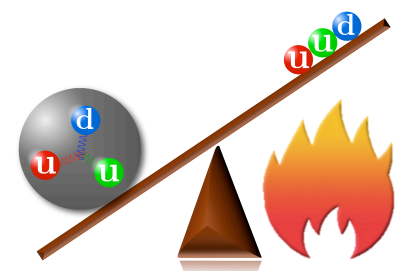
restored pattern
of **chiral** and $\mathrm{U_A(1)}$ symmetries
the nature of phase transition

Pisarski and Wilczek (1984)

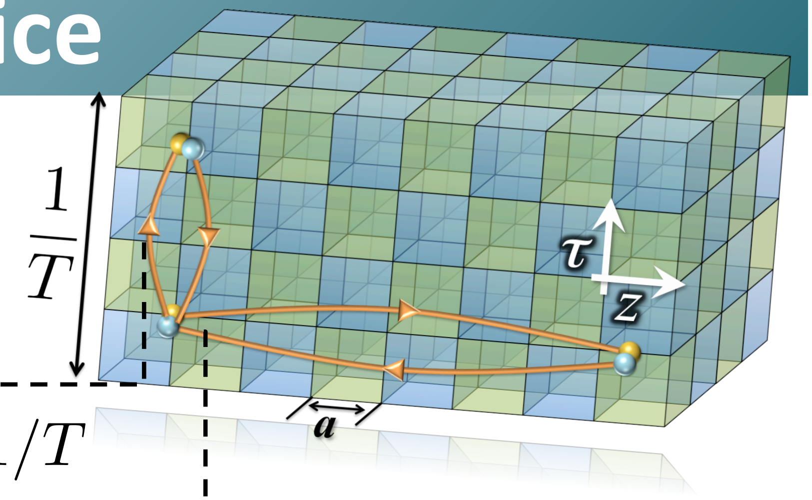


Theoretical understanding in lattice QCD simulations
from spatial correlation functions

Previous: strange-charm PRD91 (2015) 5, 054503
This work: **including up/down at widely *T* range**



Hadronic excitation on Lattice



Temporal correlation function:

$$G^T(\tau, T) = \int d^3x \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{\tau\to\infty} Ae^{-m_0\tau}$$

...difficult due to the limitation $\tau < 1/T$

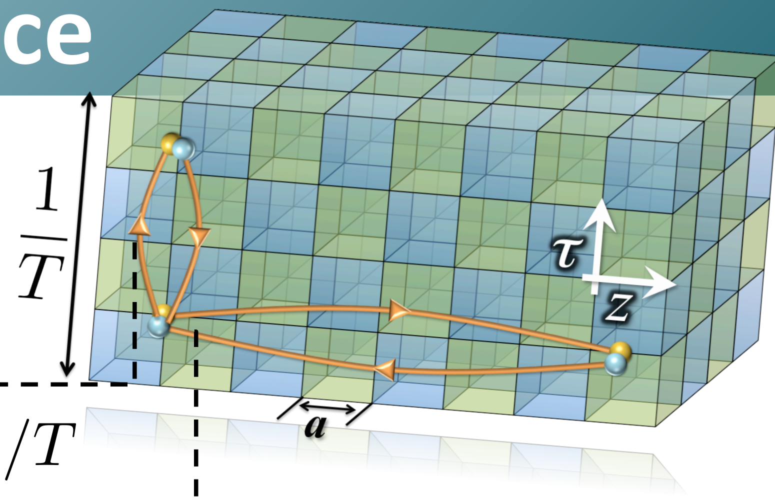
Spatial correlation function:

$$G^S(z, T) = \int_0^{1/T} d\tau \int dx dy \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{z\to\infty} Ae^{-M(T)z}$$

$M(T)$: screening mass

No limitation to spatial direction: more sensitive to in-medium modification

Hadronic excitation on Lattice



Temporal correlation function:

$$G^T(\tau,T) = \int d^3x \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{\tau\to\infty} Ae^{-m_0\tau}$$

...difficult due to the limitation $\tau < 1/T$

Spatial correlation function:

$$G^S(z,T) = \int_0^{1/T} d\tau \int dxdy \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{z\to\infty} Ae^{-M(T)z}$$

$M(T)$: screening mass

No limitation to spatial direction: more sensitive to in-medium modification

Spectral function

$$G^T(\tau,T) = \int_0^\infty d\omega \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \sigma(\omega,T)$$

e.g.) reconstruction of σ: MEM

$$G^S(z,T) = \int_0^\infty \frac{2d\omega}{\omega} \int_{-\infty}^{\infty} dp_z e^{ip_z z} \sigma(\omega,p_z,T)$$

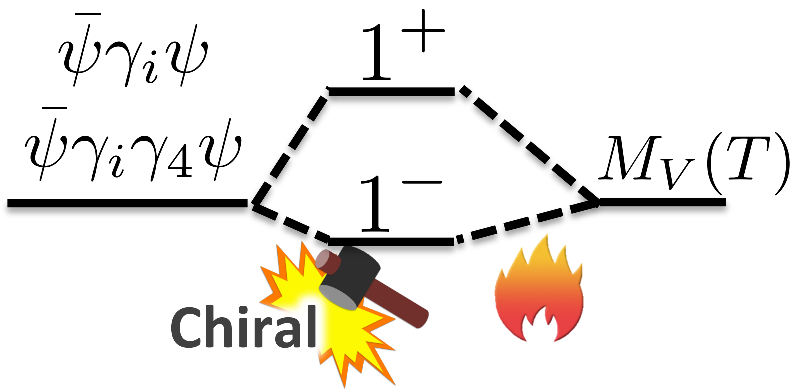
No T dependence in Kernel: direct probe of thermal modification of σ

$$G^S(z,T)/G^S(z,T=0)$$

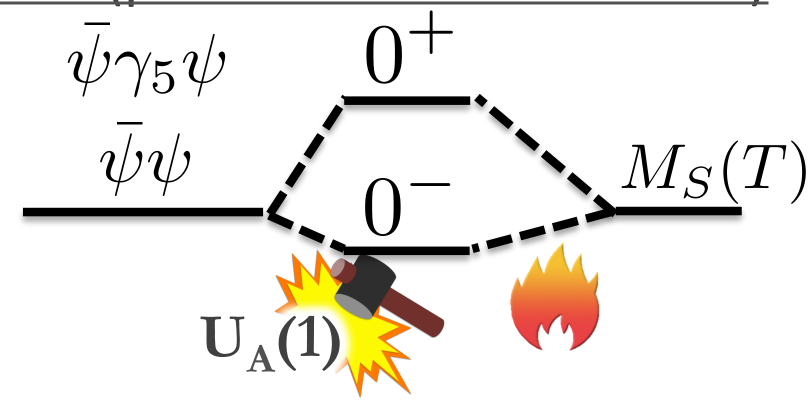
Hadronic excitation on Lattice

Parity partner of meson states

Vector (vector and axial-vector)



Scalar (pseudo-scalar and scalar)

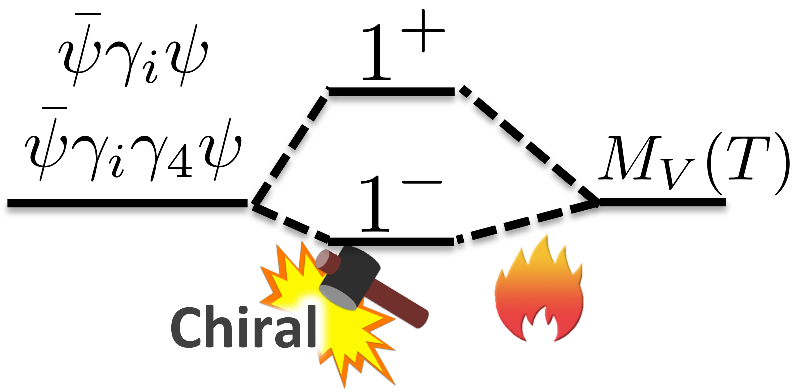


➡ Degeneracy of parity partners: indicator of symmetry restorations

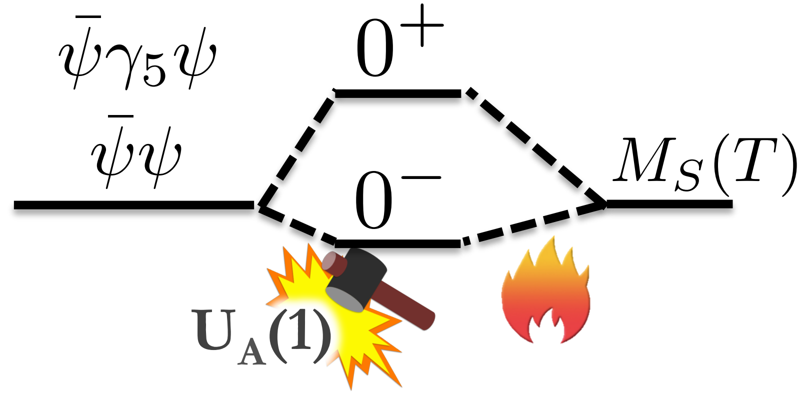
Hadronic excitation on Lattice

Parity partner of meson states

Vector (vector and axial-vector)



Scalar (pseudo-scalar and scalar)



Degeneracy of parity partners: indicator of symmetry restorations

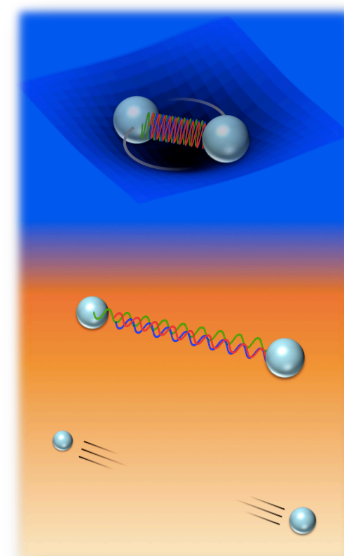
Behavior in limiting cases:

At low T, bound state: $M(T) \sim m_0$ pole mass at $T=0$

$$\sigma(\omega, 0, 0, p_z, T) \sim \delta(\omega^2 - p_z^2 - m_0^2)$$

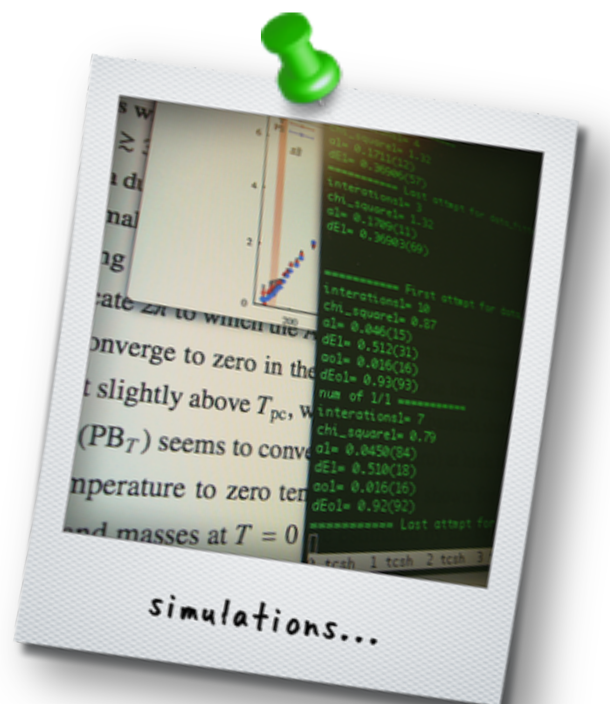
At $T \sim T_c$, in-medium modification and/or dissolution
degeneracy of parity partner states

At $T \to \infty$, free quark-antiquark pair: $M \to 2\sqrt{m_q^2 + (\pi T)^2}$
with the lowest Matsubara frequency



Lattice simulations

- Setup in HISQ
- Modifications of Mesons
- Restorations of broken symmetries



Highly Improved Staggered Quark

Reduction of taste violation
Control of cutoff effects

Bazavov et al. `11, Hot-QCD `11, `14

Lattice parameters

- 2+1 flavor QCD (charm quenched)
- m_s: physical, $m_l/m_s = 1/20$ (m_π~160 MeV, m_K~504 MeV)
- $N_\tau = 8$ (T = 110—207 MeV)
  10 (T = 139—166 MeV)
  12 (T = 149—400 MeV)
  keeping $N_s/N_\tau=4$
- 32^4--48^3x64 at $T = 0$
- scale: f_k input
- calculating quark-line connected part of meson correlators

Mesons contents

Γ	J^P	$u\bar{d}$	$u\bar{s}$	$u\bar{c}$	$s\bar{s}$	$s\bar{c}$	$c\bar{c}$
γ_5	0^-	π	K	D	$(\eta_{s\bar{s}})$	D_s	η_c
1	0^+	–	K_0^*	D_0^*	–	D_{s0}^*	χ_{c0}
γ_i	1^-	ρ	K^*	D^*	ϕ	D_s^*	J/ψ
$\gamma_i\gamma_5$	1^+	–	K_1	D_1	$f_1(1420)$	D_{s1}	χ_{c1}

Highly Improved Staggered Quark

Reduction of taste violation

Control of cutoff effects

Bazavov et al. `11, Hot-QCD `11, `14

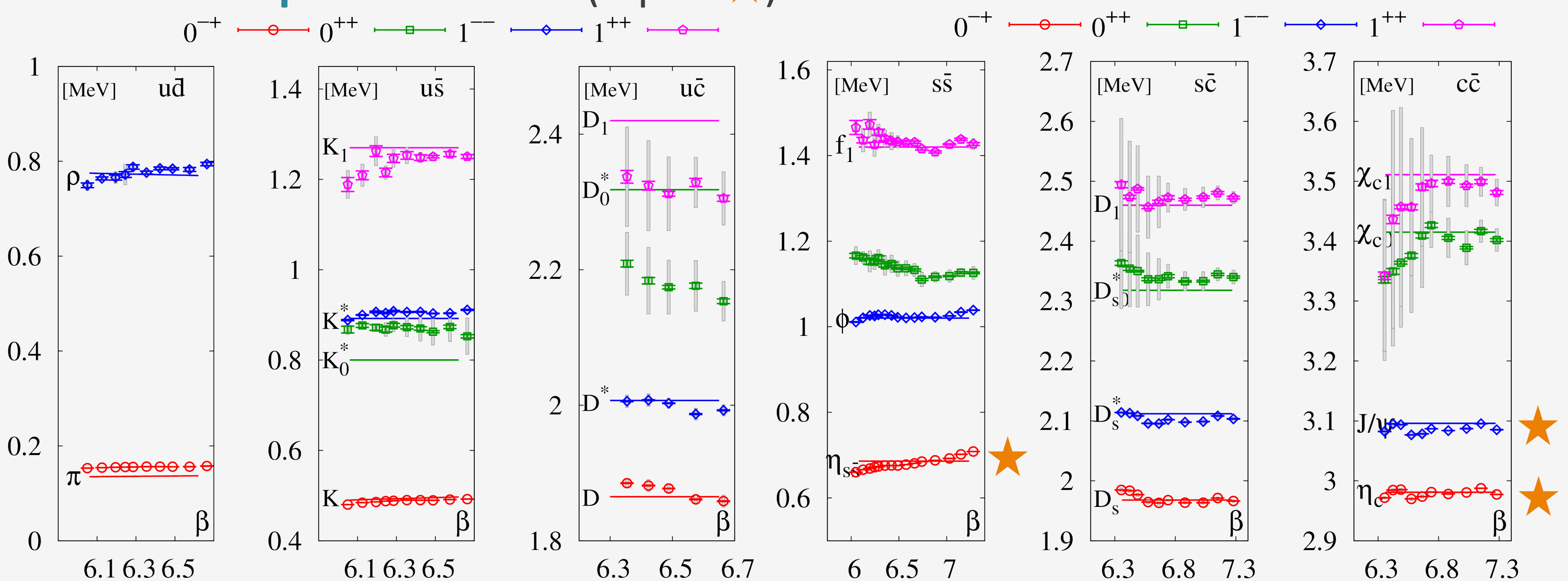
<u>Lattice parameters</u>

- 2+1 flavor QCD (charm quenched)
- m_s: physical, $m_l/m_s = 1/20$

Mesons contents

Γ	J^P	$u\bar{d}$	$u\bar{s}$	$u\bar{c}$	$s\bar{s}$	$s\bar{c}$	$c\bar{c}$
γ_5	0^-	π	K	D	$(\eta_{s\bar{s}})$	D_s	η_c
1	0^+	–	K_0^*	D_0^*	–	D_{s0}^*	χ_{c0}
γ_i	1^-	ρ	K^*	D^*	ϕ	D_s^*	J/ψ
$\gamma_i\gamma_5$	1^+	–	K_1	D_1	$f_1(1420)$	D_{s1}	χ_{c1}

Meson spectra at T = 0 (input: ★)



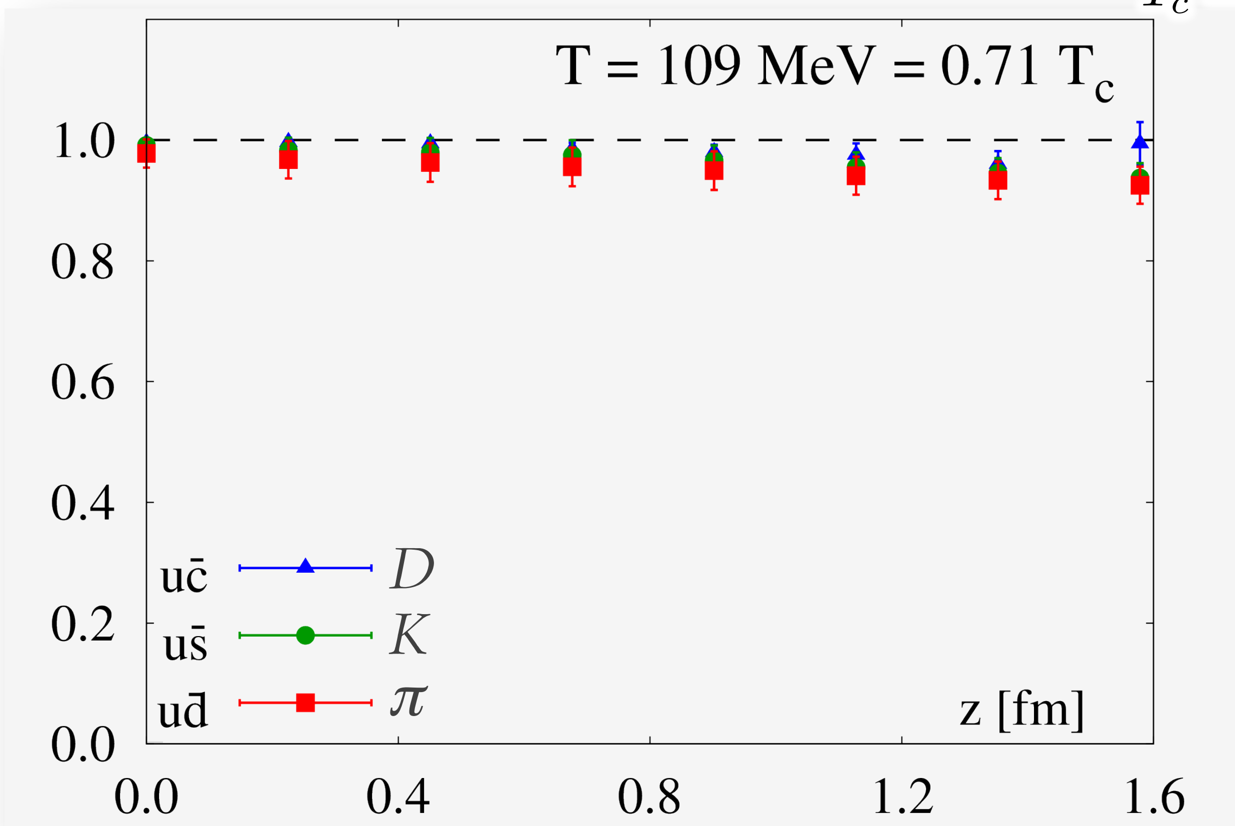
Ratio of spatial correlation functions

Probe of thermal modifications of spectral function

$G^S(z,T)/G^S(z,T=0) \simeq 1$ the same σ at $T=0$, or $\neq 1$ modified

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar
$J^P = 0^-$



- $G^S(z,T)/G^S(z,0) \simeq 1$ at short distance ➡ physics: not sensitive to T
- $G^S(z,T)/G^S(z,0) \neq 1$ at large distance ➡ thermal modification of σ

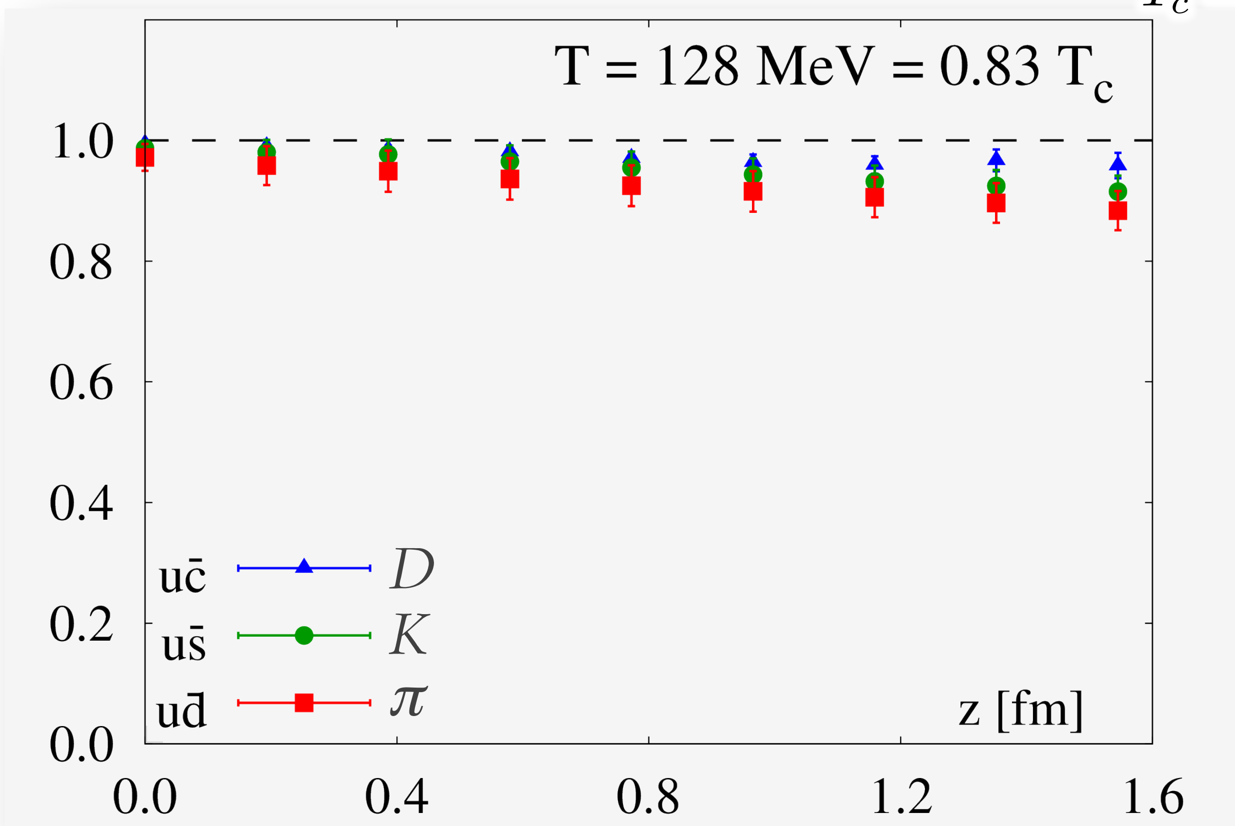
Ratio of spatial correlation functions

Probe of thermal modifications of spectral function

$G^S(z,T)/G^S(z,T=0) \simeq 1$ the same σ at $T=0$, or $\neq 1$ modified

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar
$J^P = 0^-$



- $G^S(z,T)/G^S(z,0) \simeq 1$ at short distance ➡ physics: not sensitive to T
- $G^S(z,T)/G^S(z,0) \neq 1$ at large distance ➡ thermal modification of σ

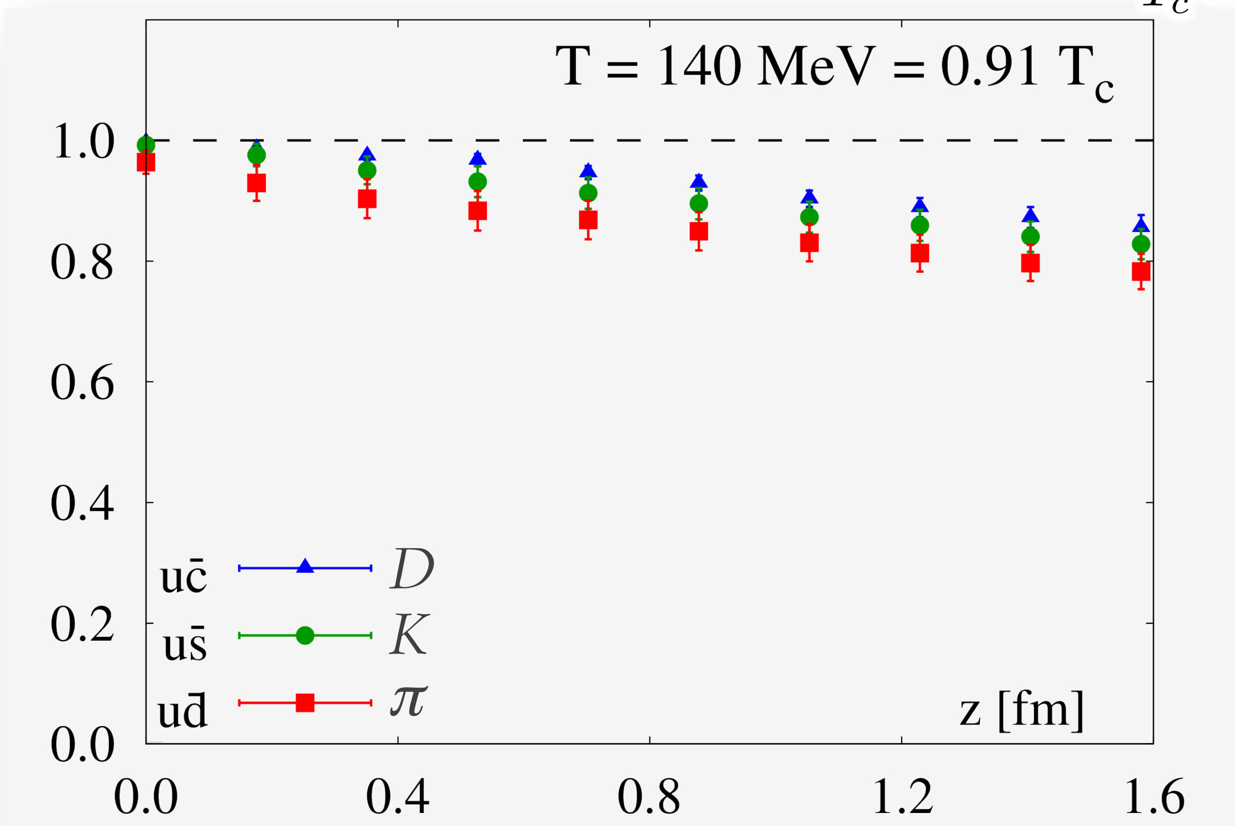
Ratio of spatial correlation functions

Probe of thermal modifications of spectral function

$G^S(z,T)/G^S(z,T=0) \simeq 1$ the same σ at $T=0$, or $\neq 1$ modified

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar
$J^P = 0^-$



- $G^S(z,T)/G^S(z,0) \simeq 1$ at short distance ➡ physics: not sensitive to T
- $G^S(z,T)/G^S(z,0) \neq 1$ at large distance ➡ thermal modification of σ
- modification at $T < T_c$

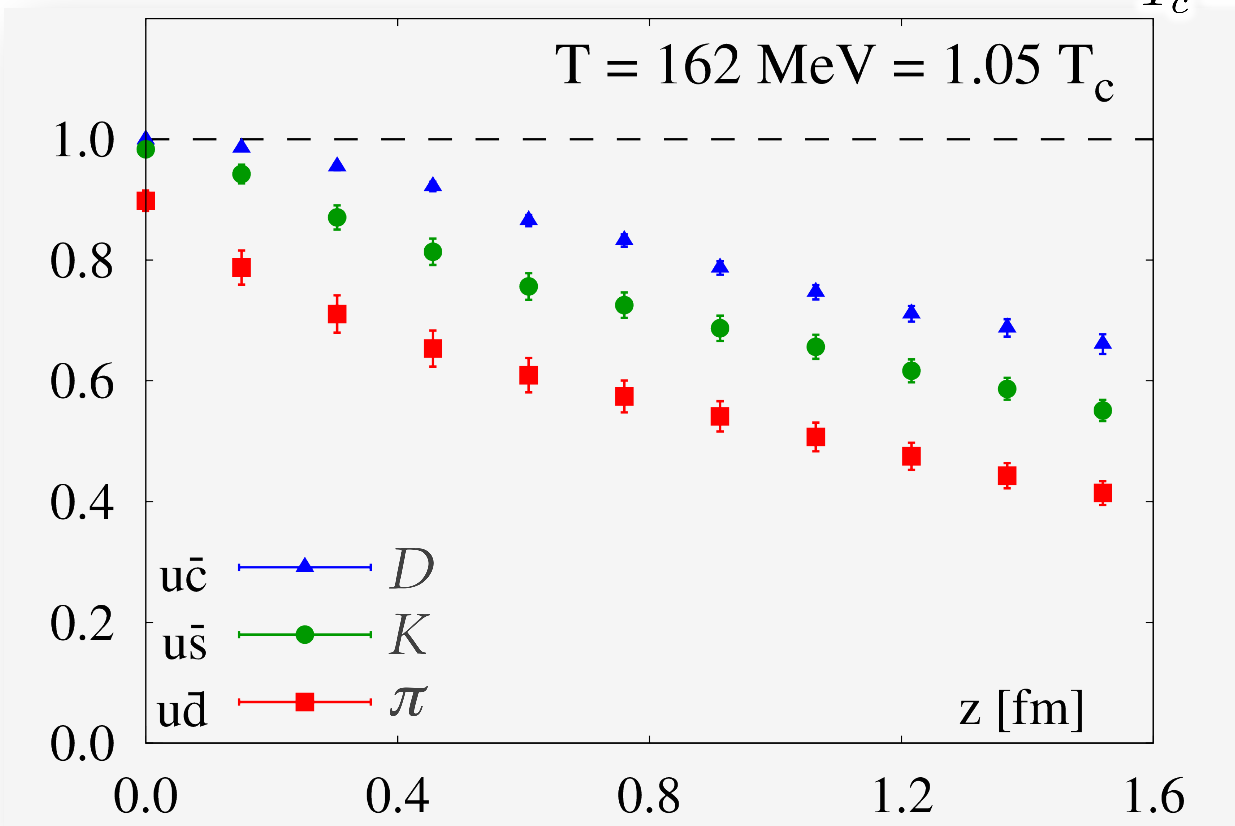
Ratio of spatial correlation functions

Probe of thermal modifications of spectral function

$G^S(z,T)/G^S(z,T=0) \simeq 1$ the same σ at $T=0$, or $\neq 1$ modified

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar
$J^P = 0^-$



- $G^S(z,T)/G^S(z,0) \simeq 1$ at short distance ➡ physics: not sensitive to T
- $G^S(z,T)/G^S(z,0) \neq 1$ at large distance ➡ thermal modification of σ
- modification at $T < T_c$, explicit flavor dependence at $T > T_c$

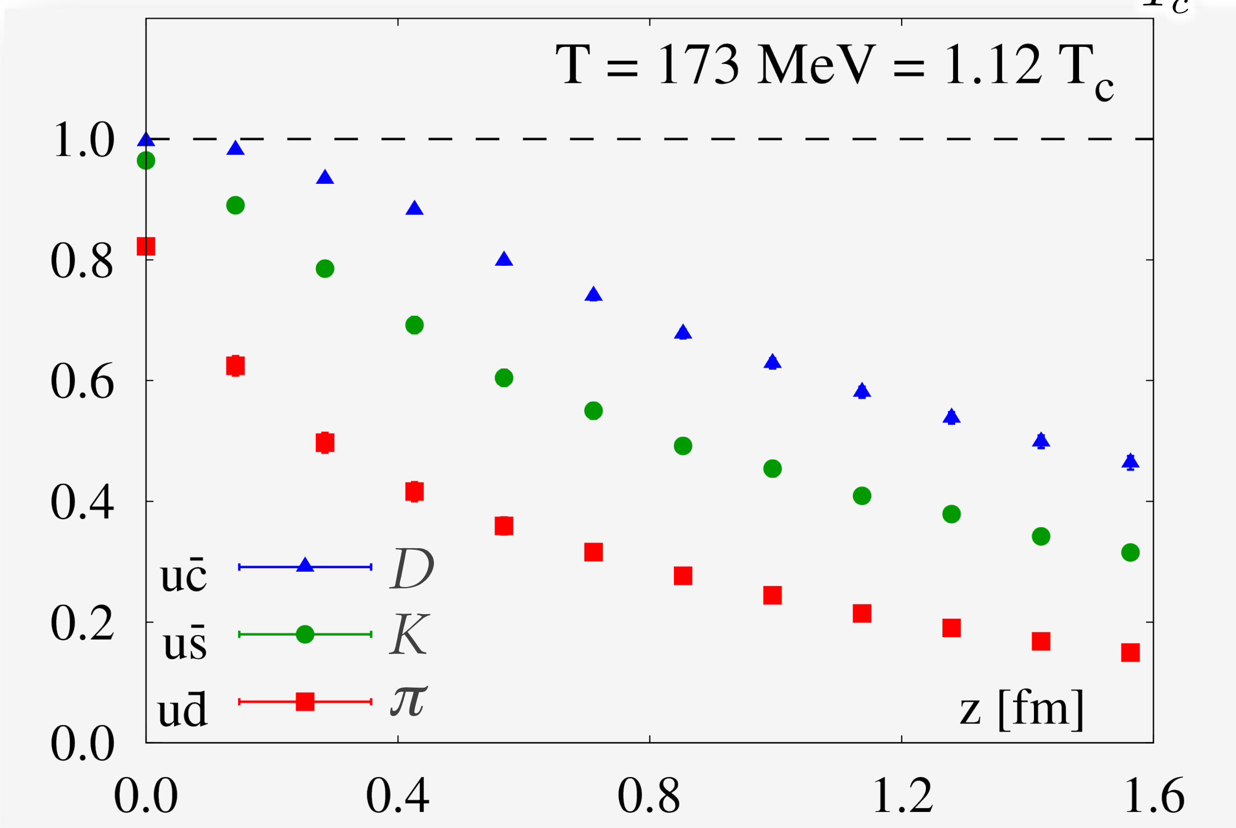
Ratio of spatial correlation functions

Probe of thermal modifications of spectral function

$G^S(z,T)/G^S(z,T=0) \simeq 1$ the same σ at $T=0$, or $\neq 1$ modified

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar
$J^P = 0^-$

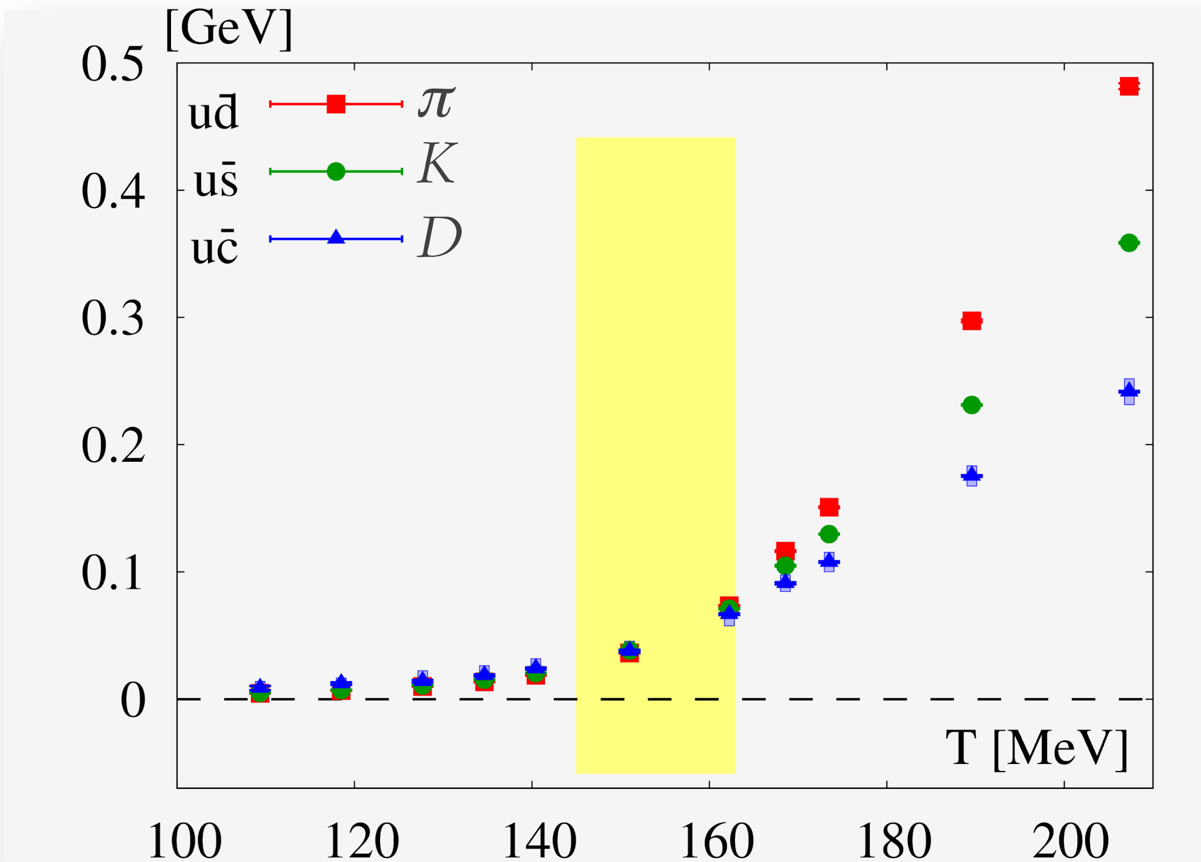


- $G^S(z,T)/G^S(z,0) \simeq 1$ at short distance ➡ physics: not sensitive to T
- $G^S(z,T)/G^S(z,0) \neq 1$ at large distance ➡ thermal modification of σ
- modification at $T < T_c$, explicit flavor dependence at $T > T_c$

Mass difference

$$\Delta M(T) = M(T) - m_0$$ ~ **change of "binding energy"**

Pseudo-scalar
$J^P = 0^-$



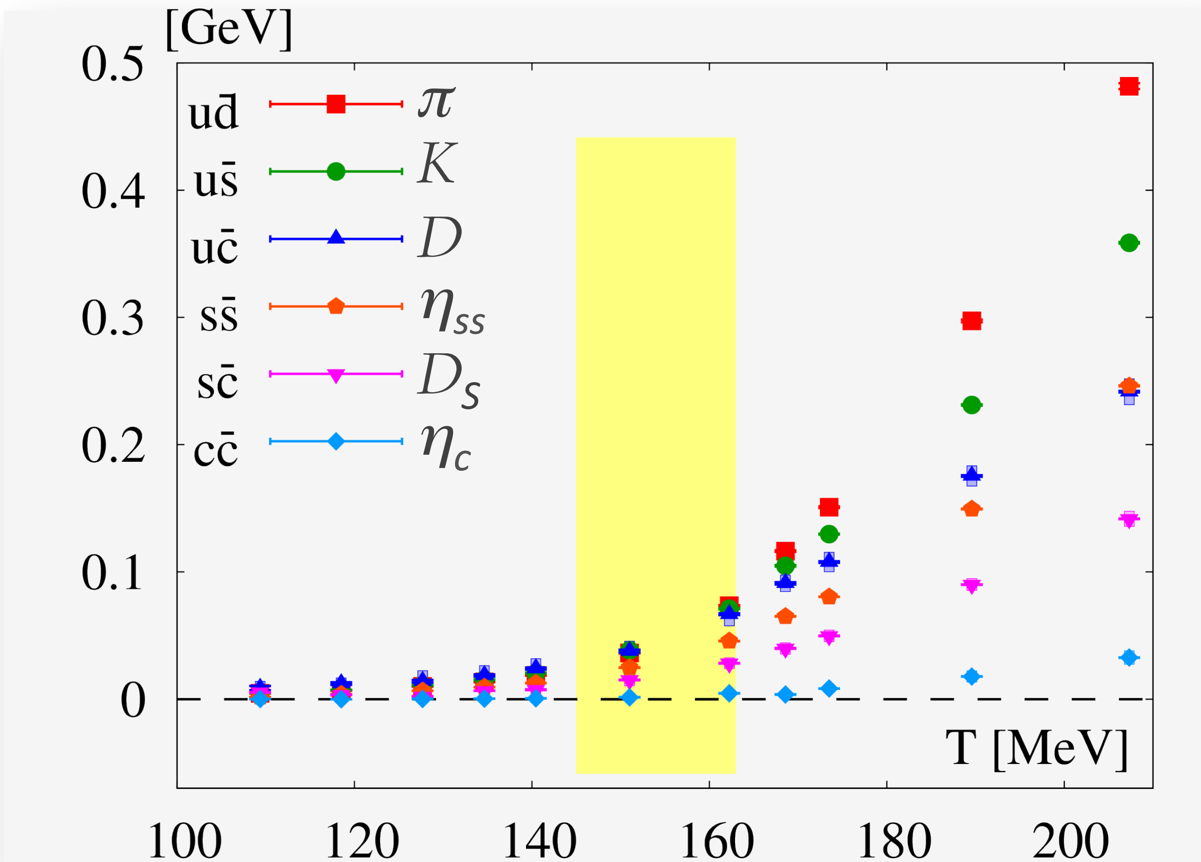
- $u\bar{d},\ u\bar{s},\ u\bar{c}$: explicit thermal modification below T_c,

  similar modification pattern at $T < T_c$,
  explicit flavor dependence at $T > T_c$

Mass difference

$\Delta M(T) = M(T) - m_0$ ~ **change of "binding energy"**

Pseudo-scalar
$J^P = 0^-$



- $u\bar{d},\ u\bar{s},\ u\bar{c}$: explicit thermal modification below T_c,
  - ➡ similar modification pattern at $T < T_c$,
    explicit flavor dependence at $T > T_c$
- $s\bar{s},\ s\bar{c}$: slight modification below T_c
- $c\bar{c}$: stable beyond T_c

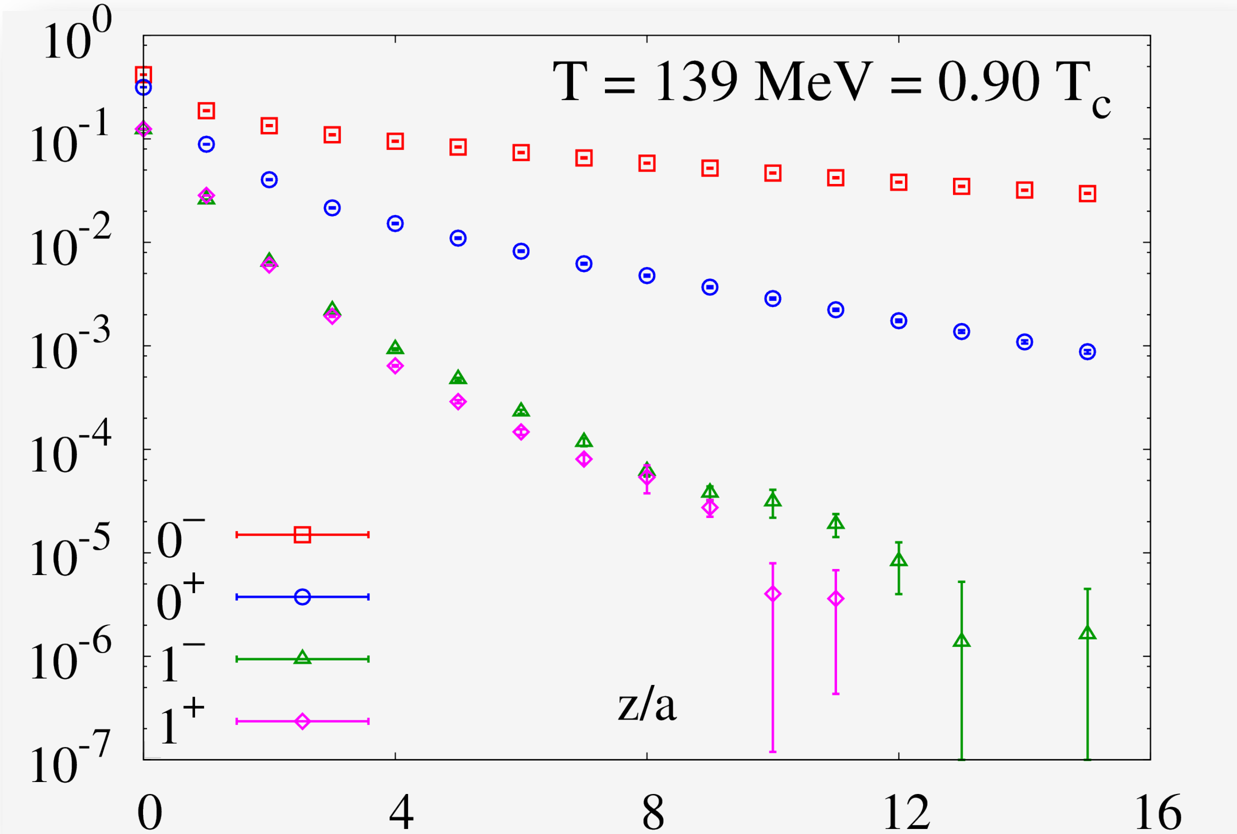
PRD91 (2015) 5, 054503

Restoration of broken symmetries

Degeneracy of vector partners ➔ restoration of chiral symmetry

Degeneracy of scalar partners ➔ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$

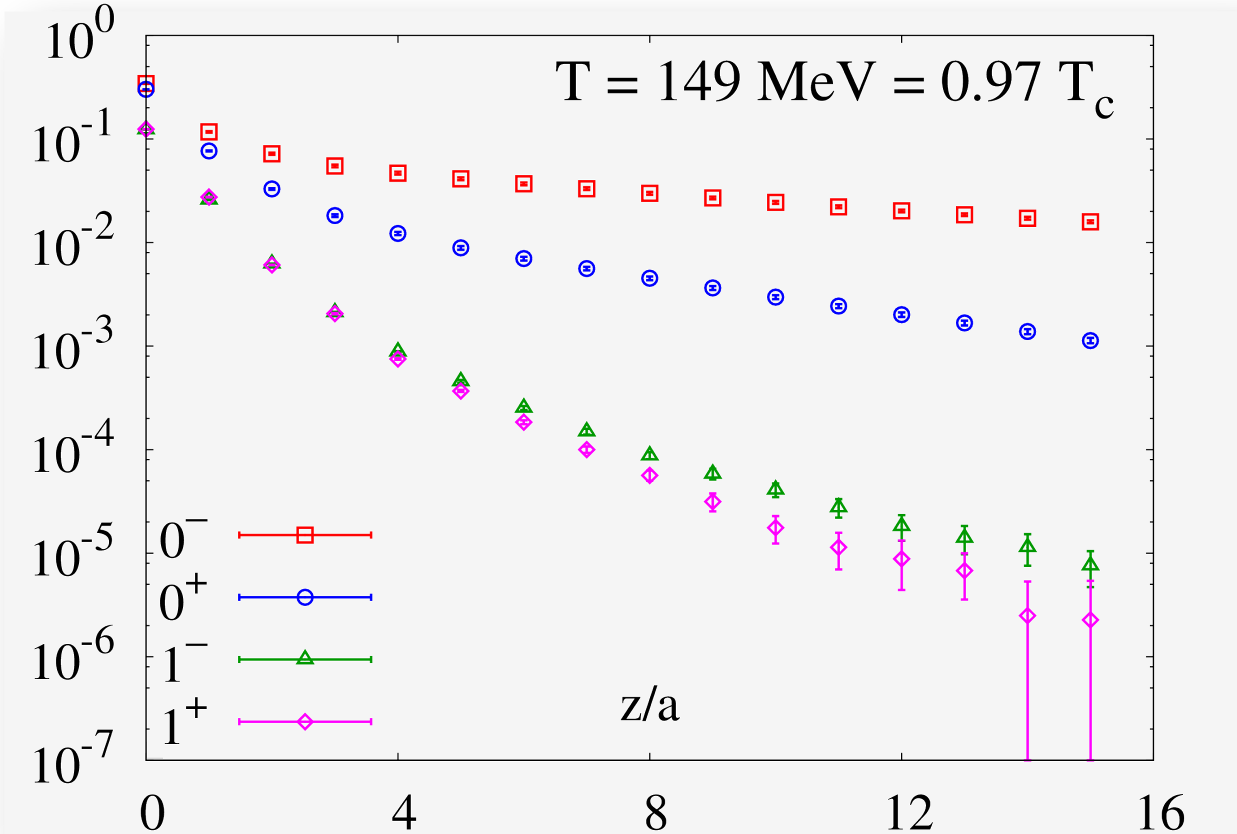


Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$

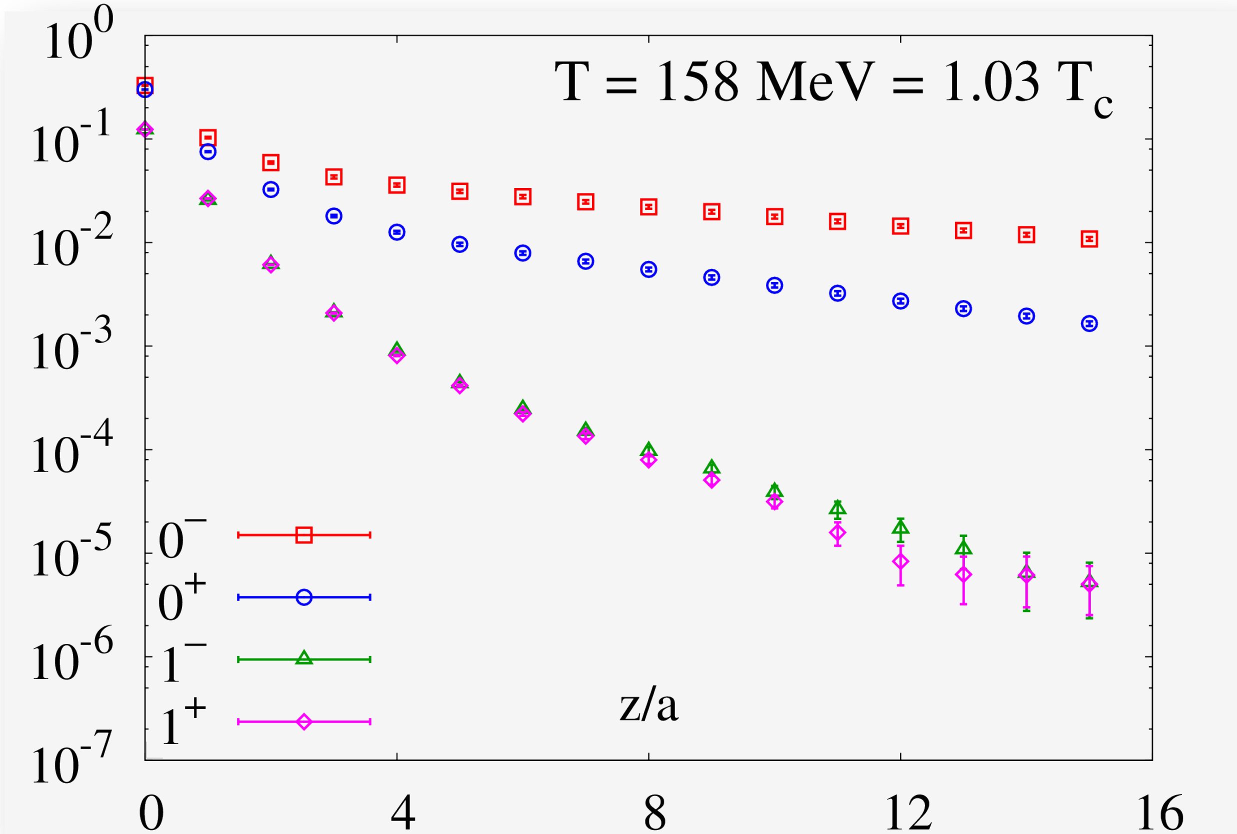


Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$



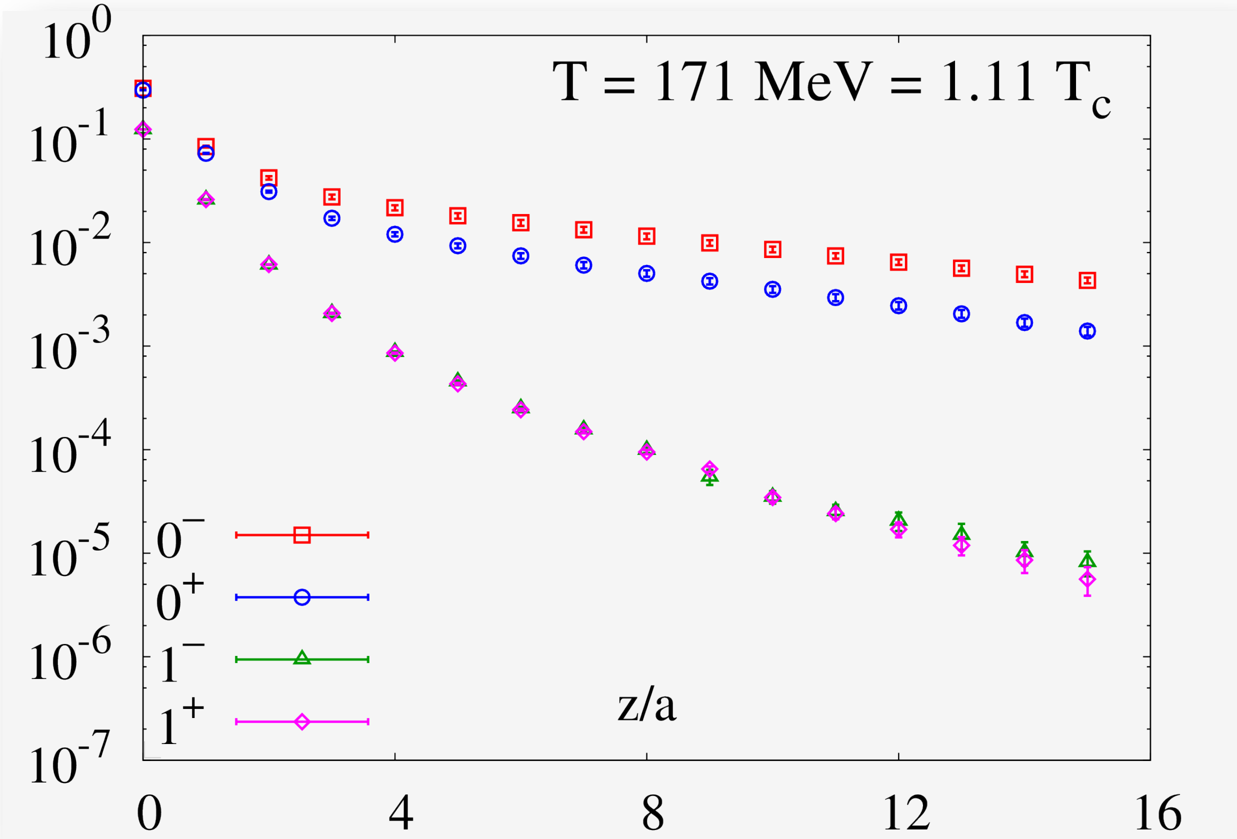
- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A}(1)$ symmetry

$G^S(z,T)$



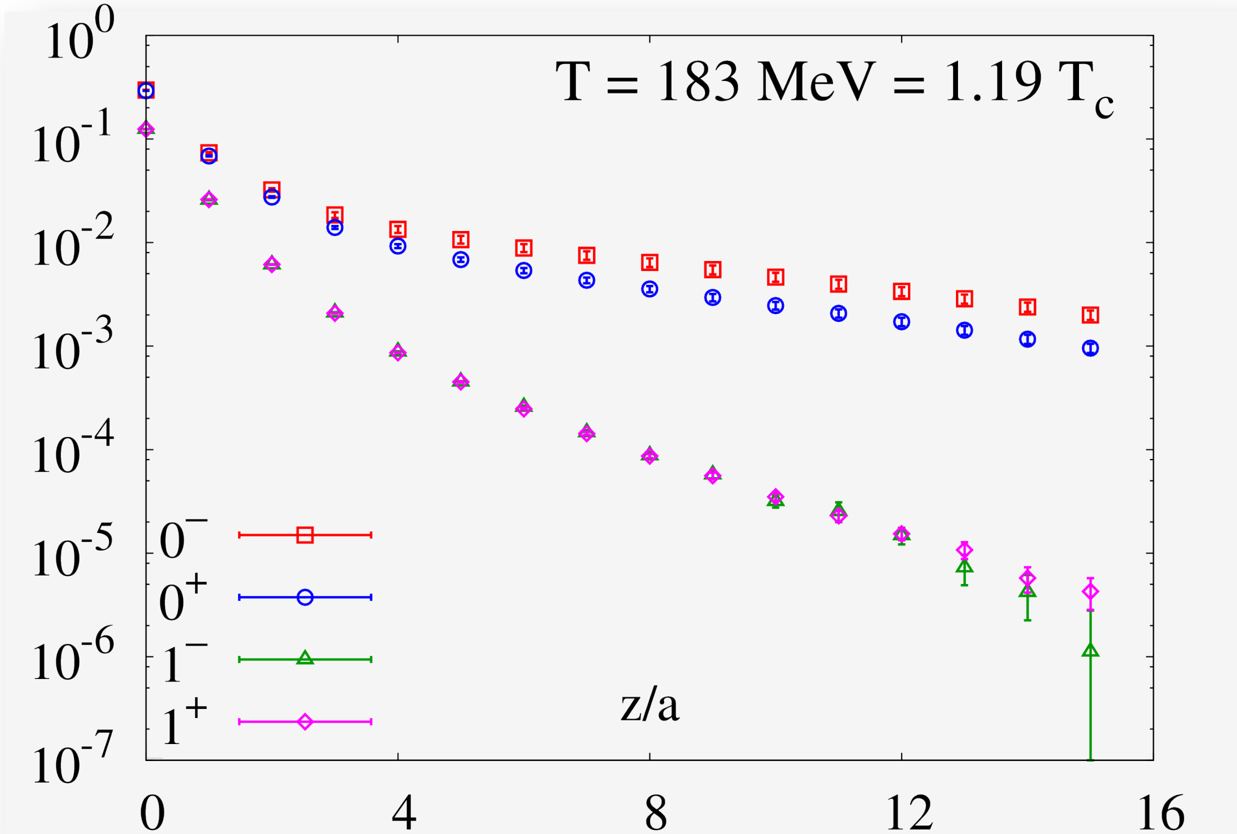
- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$



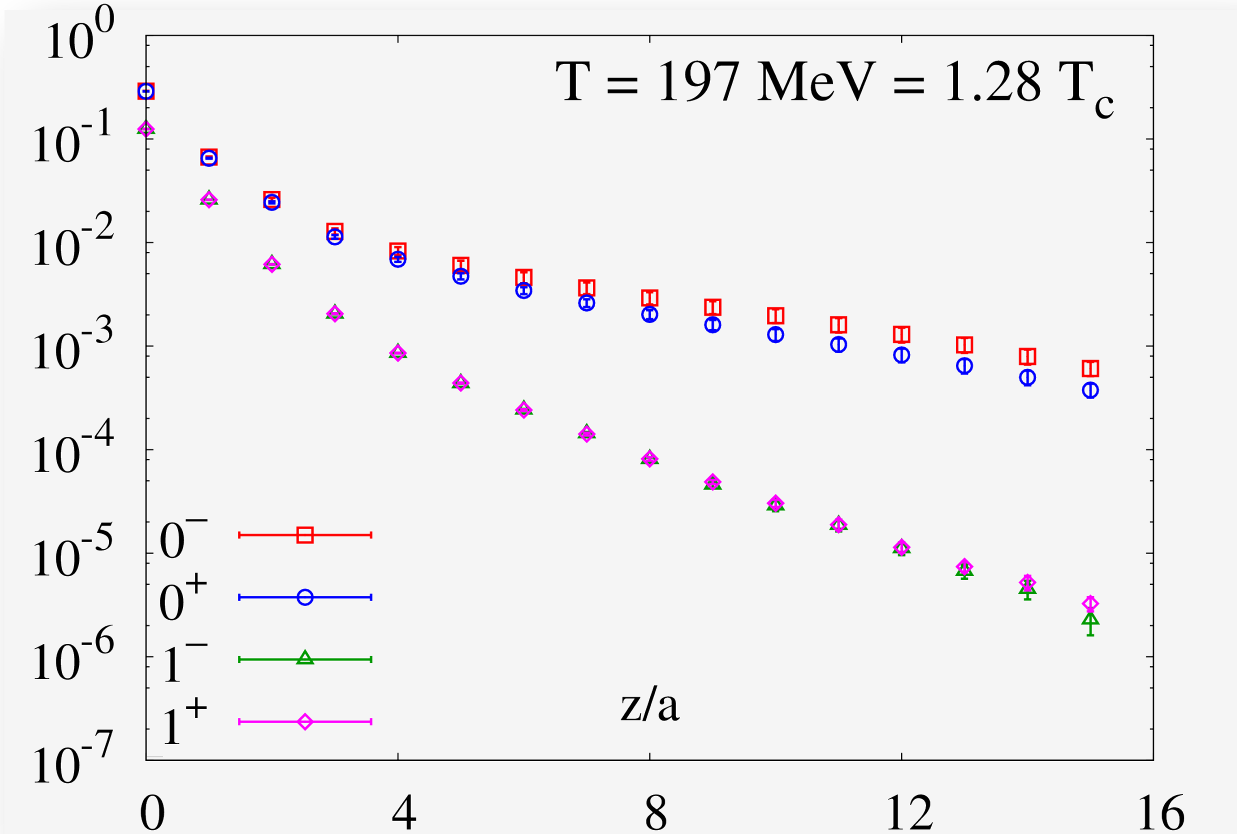
- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$



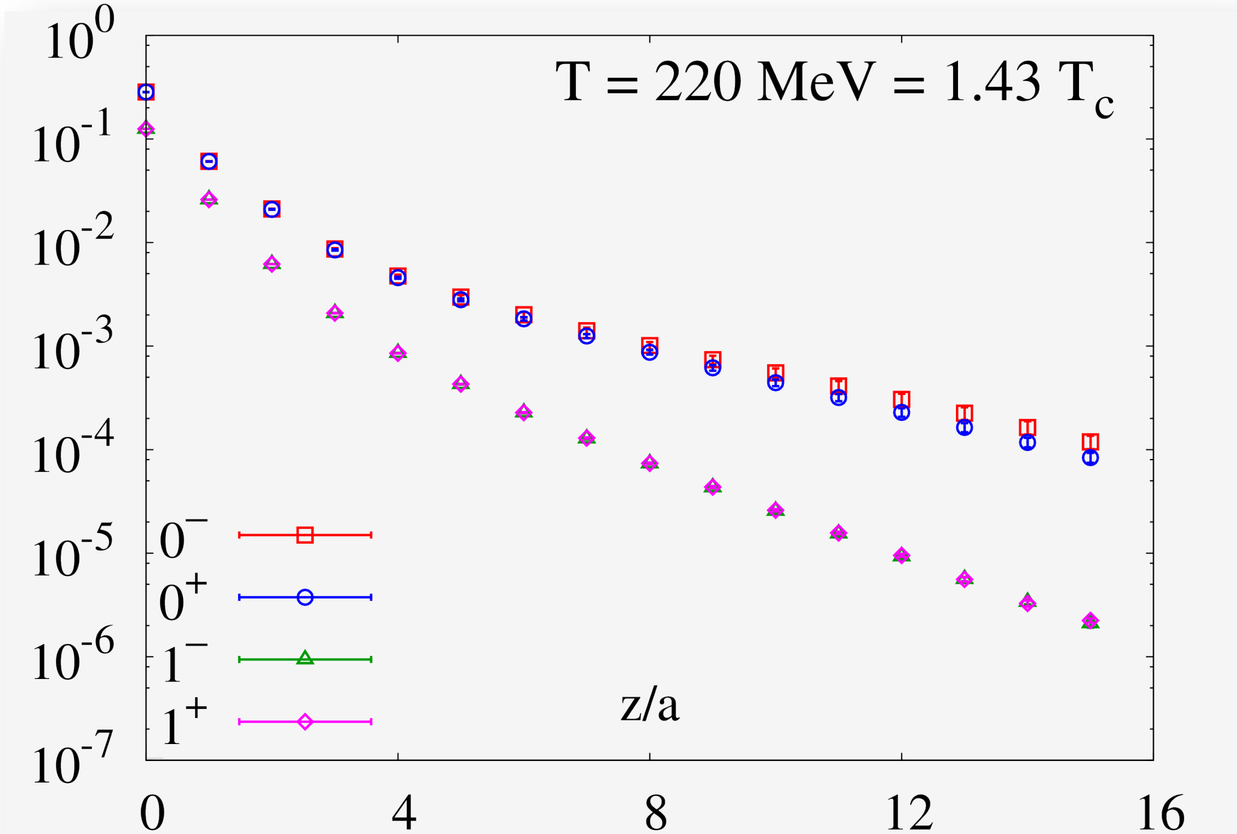
- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$

Restoration of broken symmetries

Degeneracy of vector partners → restoration of chiral symmetry

Degeneracy of scalar partners → (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$



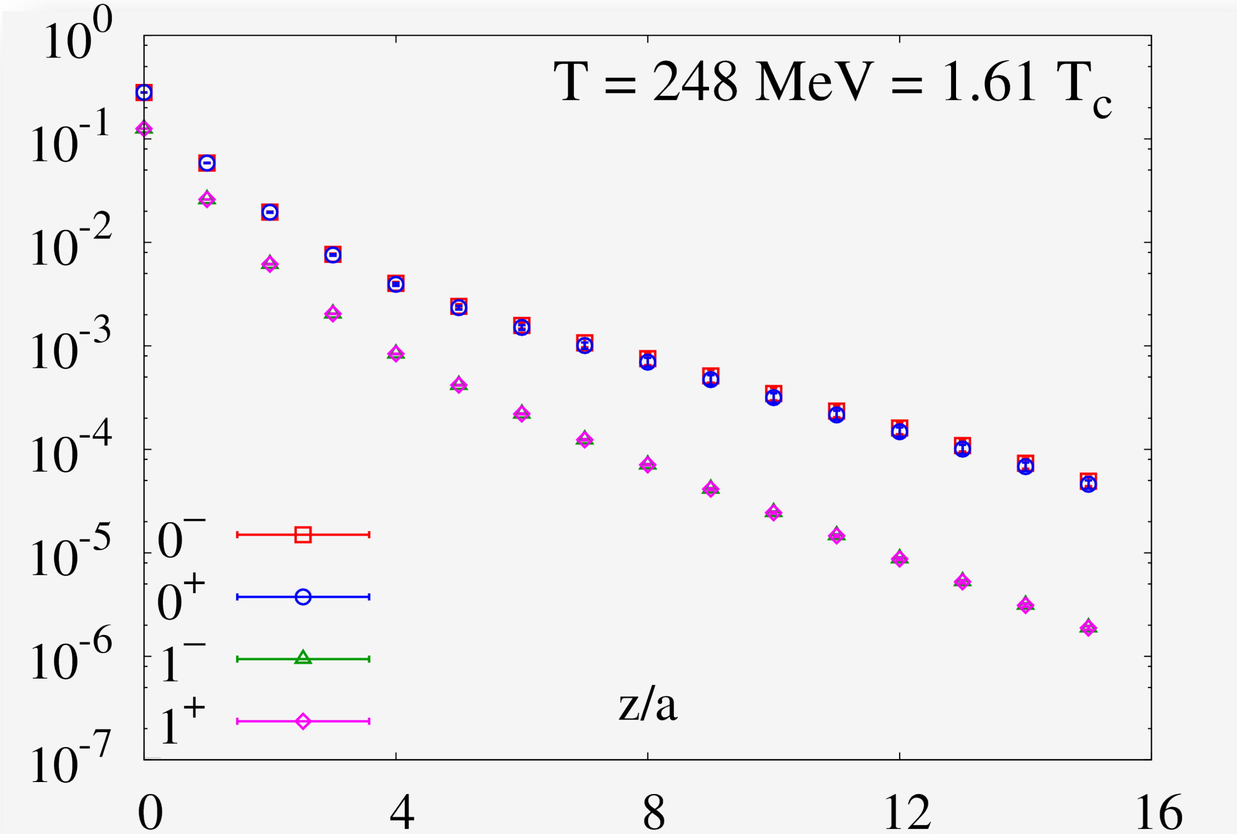
- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$
- Scalar partner degenerates at $T \sim 1.4T_\mathrm{c}$--$1.6T_\mathrm{c}$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$

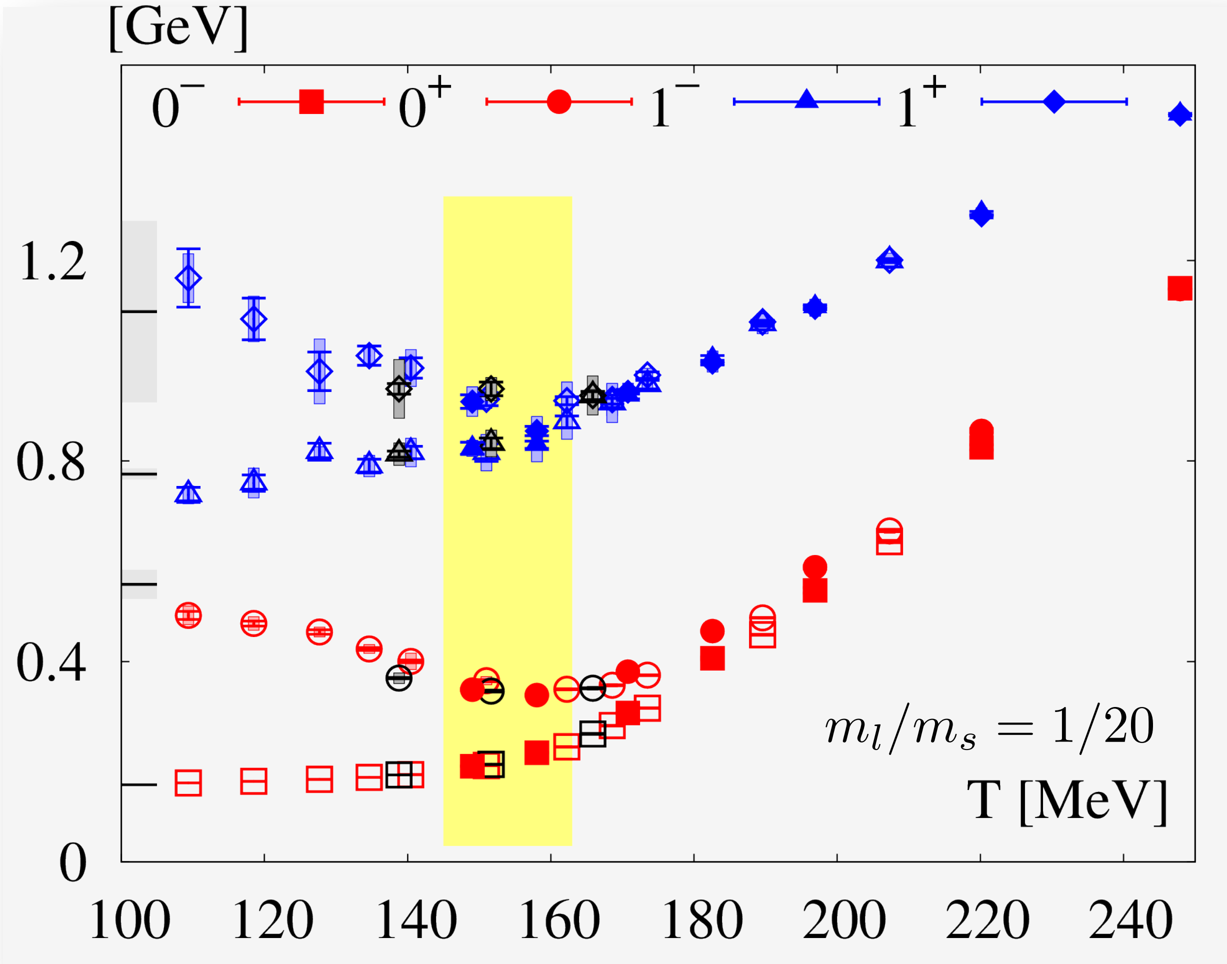


- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$
- Scalar partner degenerates at $T \sim 1.4T_c$--$1.6T_c$

Restoration of broken symmetries

Large distance behavior of spatial correlator $G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

Light-unflavored
$u\bar{d}$



Open: $N\tau = 8$
Black: $N\tau = 10$
Filled: $N\tau = 12$

- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$
- Scalar partner degenerates at $T \sim 1.4T_c$--$1.6T_c$

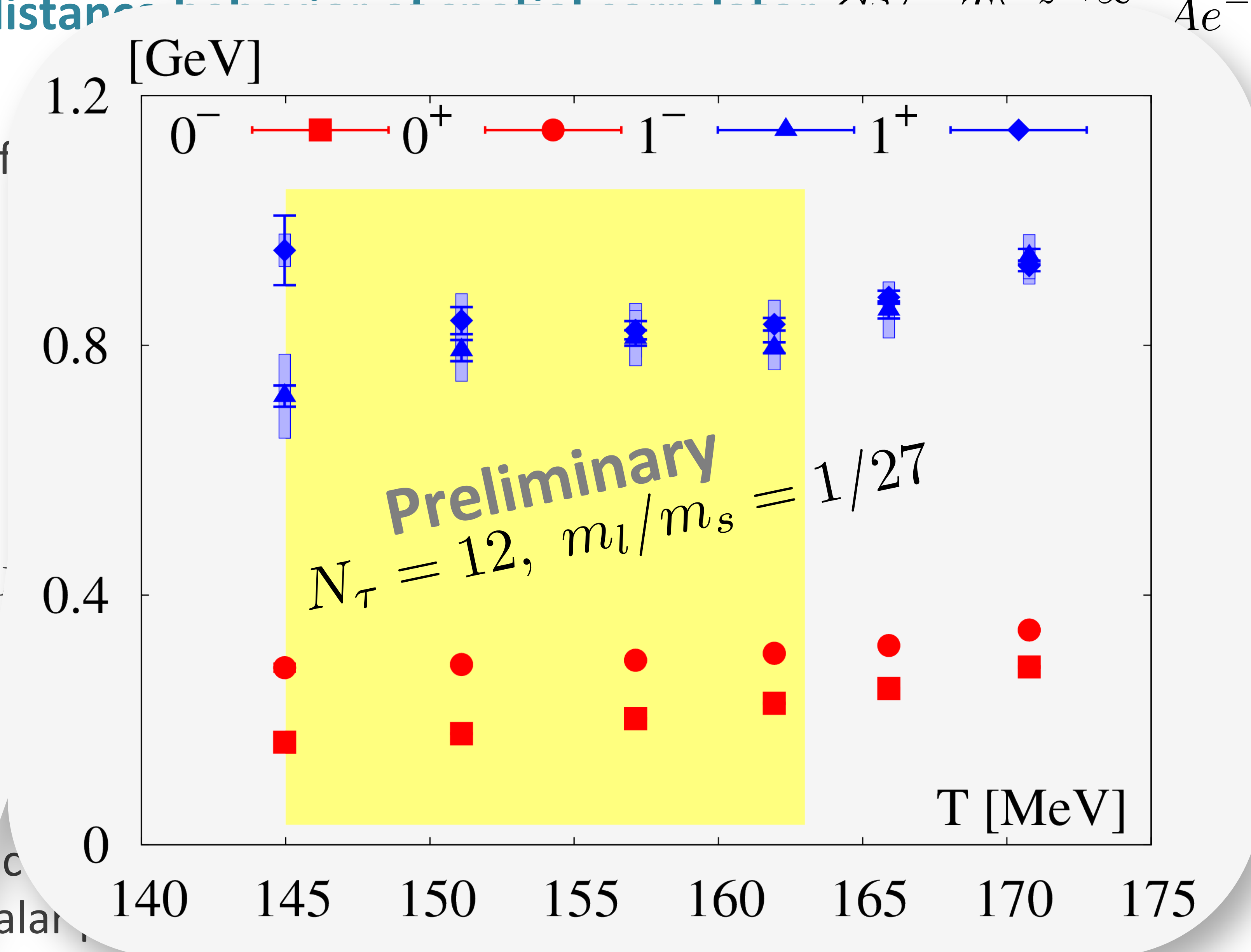
➡ chiral: restored, $U_A(1)$: broken at T_c, no dependence on lattice spacing

Restoration of broken symmetries

Large distan $G^S(\ldots T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

Light-unf

Open:
Black:
Filled:



- Vec
- Scalar

➡ chiral: restored, $U_A(1)$: broken at T_c, no dependence on lattice spacing

Summary

In-medium mesons from spatial correlation function

➡ Sensitive to thermal effect at finite T on lattice

- Direct probe of modification of meson spectral function
- Indicator of restorations of broken symmetries

(2+1)-flavor QCD lattice simulations with HISQ of

ratio: $G^S(z,T)/G^S(z,T=0)$, screening mass: $G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

- $u\bar{d},\ u\bar{s},\ u\bar{c}$: explicit thermal modification below T_c,

  ➡ similar modification pattern below T_c, explicit flavor dependence above T_c
- $s\bar{s},\ s\bar{c}$: slight modification below T_c
- $c\bar{c}$: stable beyond T_c

PRD91 (2015) 5, 054503

- Degeneracies of chiral partners

  ➡ chiral: restored, $\mathrm{U_A(1)}$: broken at T_c

  in continuum and physical quark mass (preliminary)

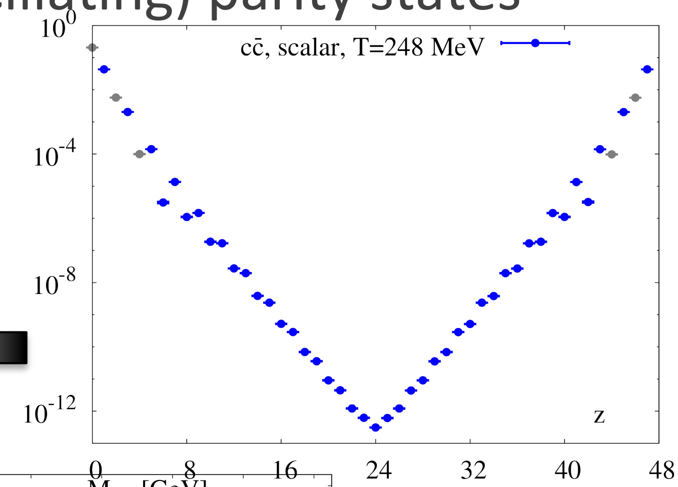
Backup slides

PRD91 (2015) 5, 054503

Effective propagator in staggered action

Including negative (non-oscillating) and positive (oscillating) parity states

$$G(z) = A_{NO}^2 e^{-M_- z} - (-1)^z A_O^2 e^{-M_+ z}$$



Parameters: obtained by four successive data

$$g_i \equiv G(z+i) \text{ with } i = 0, 1, 2, 3$$

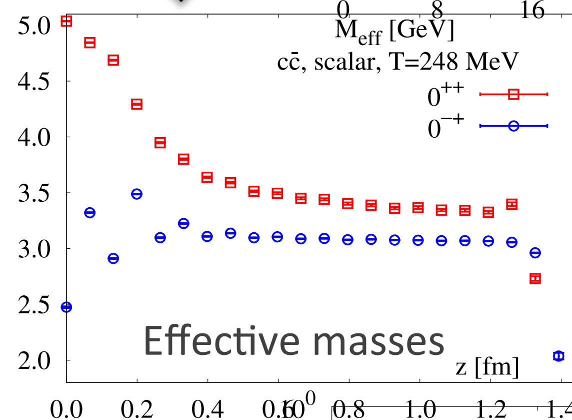
Effective masses $x_\pm \equiv e^{-M_\pm}$

in quadratic equations:

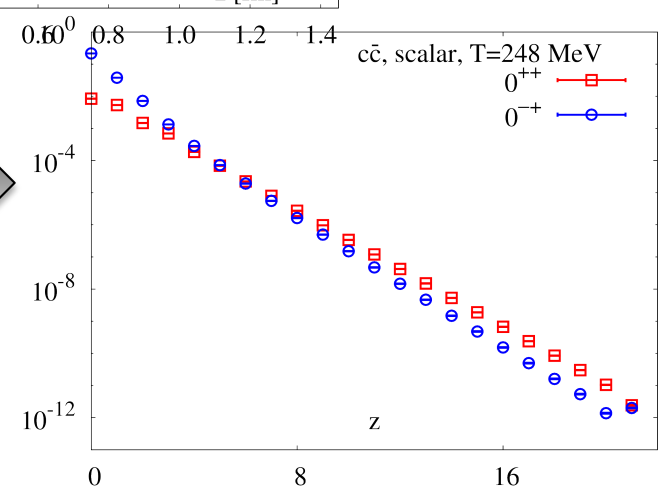
$$Ax_\pm^2 \mp Bx_\pm + C = 0$$

$$\longrightarrow \quad x_\pm = \pm\frac{B}{2A} + \frac{\sqrt{B^2 - 4AC}}{2|A|}$$

$$A = g_1^2 - g_2 g_0,\ B = g_3 g_0 - g_2 g_1,\ C = g_2^2 - g_3 g_1$$



Then the effective correlators reconstructed:



$$G_{NO}(z) \equiv A_{NO}^2(z) e^{-M_-(z)z} = \frac{g_1 + g_0 x_+}{x_- + x_+}$$

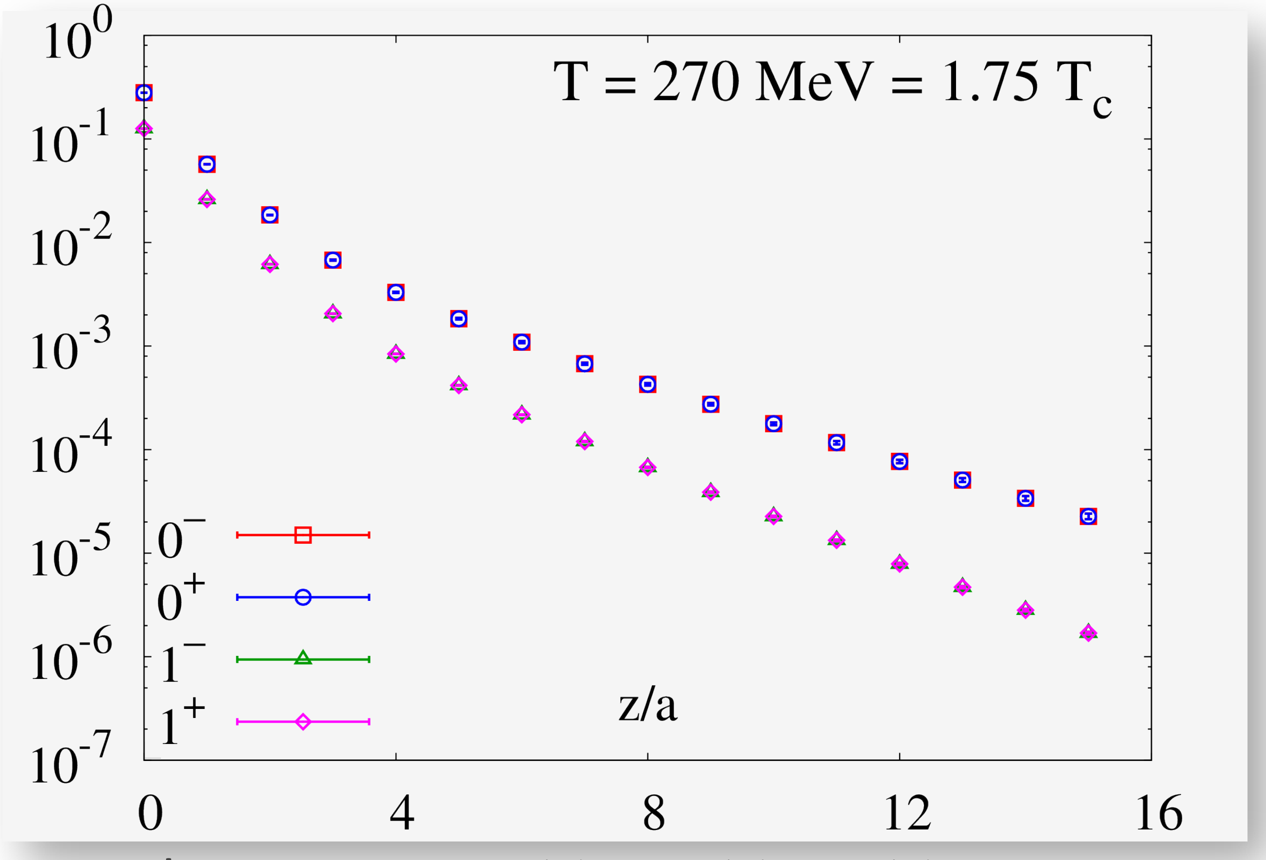
$$G_O(z) \equiv A_O^2(z) e^{-M_+(z)z} = (-1)^z \frac{g_1 - g_0 x_-}{x_- + x_+}$$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$



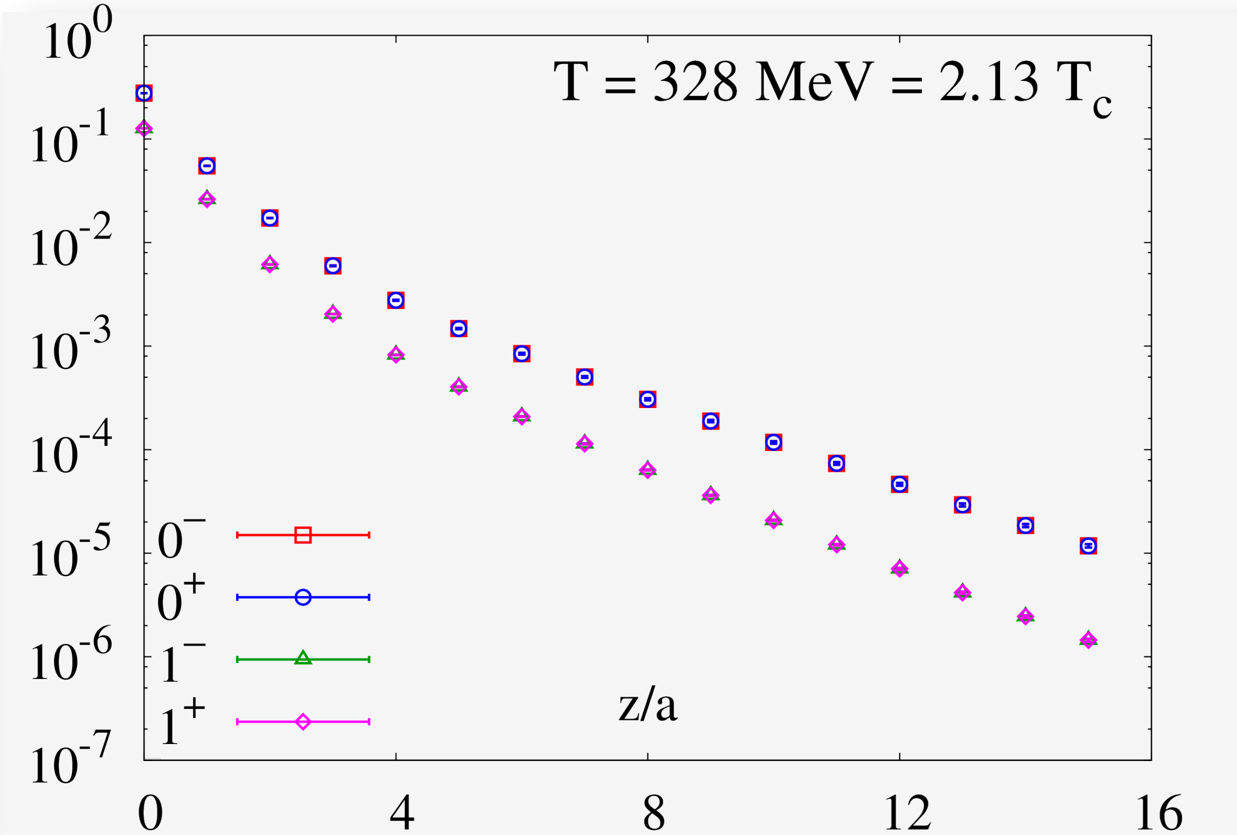
- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$
- Scalar partner degenerates at $T \sim 1.4T_\mathrm{c}$--$1.6T_\mathrm{c}$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z,T)$



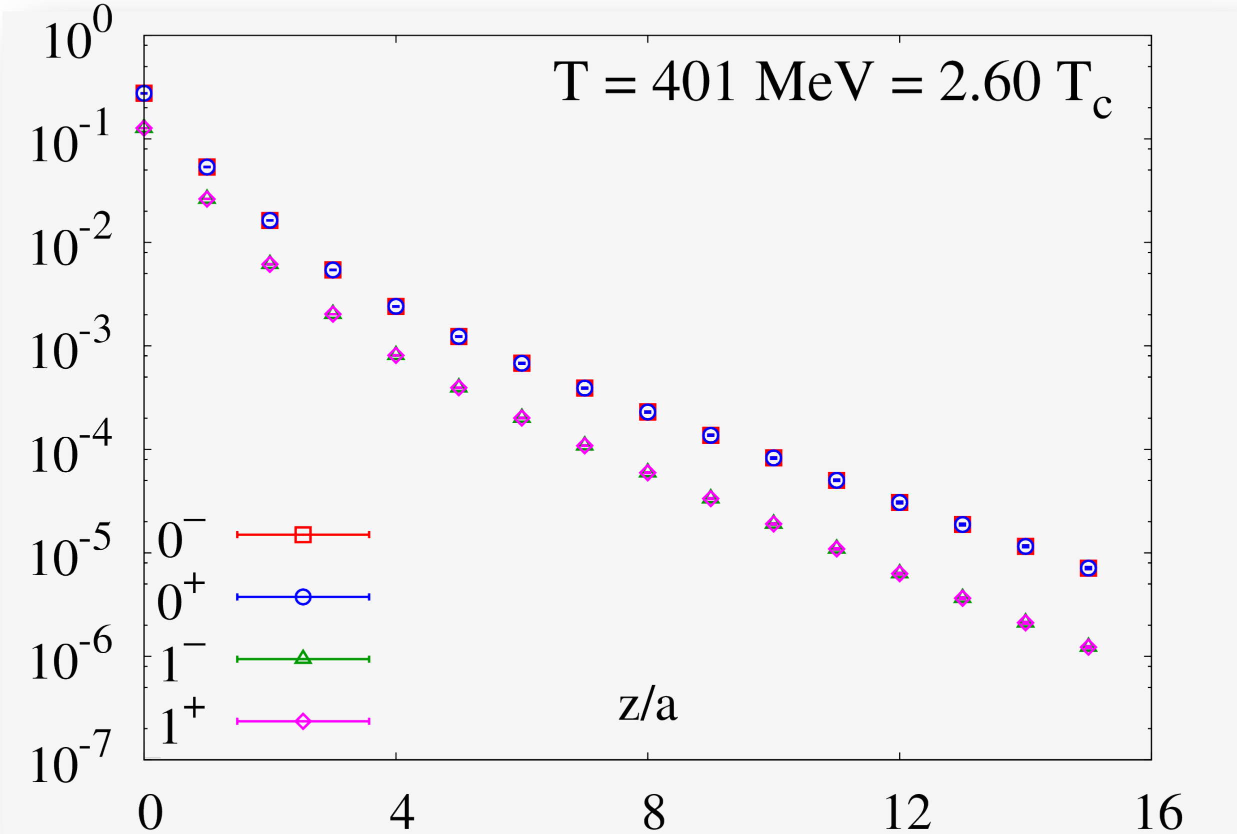
- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$
- Scalar partner degenerates at $T \sim 1.4T_c$--$1.6T_c$

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$G^S(z, T)$



- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$
- Scalar partner degenerates at $T \sim 1.4T_\mathrm{c}$--$1.6T_\mathrm{c}$
- Spin dependence explicit at $T \sim 2.6T_\mathrm{c}$

cf.) Thermal perturbation: no channel dependence Laine et al. 2004