# Fate of meson states and broken symmetries at finite temperature in lattice QCD simulations

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in collaboration with

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Computational Physics for High-Energy Heavy-Ion Collisions, YITP, Oct. 5, 2015

# Introduction

## Thermal fluctuation in QCD

### Modifications of hadrons

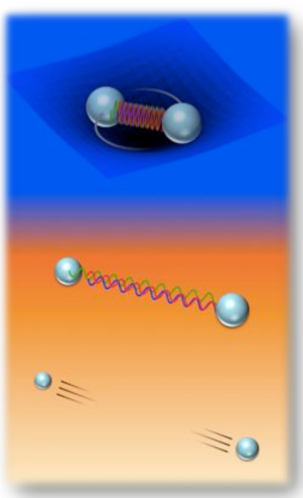
sequential melting pattern
of **quarkonium** and
**open-flavor** mesons
e.g. $J/\psi$ suppression

Matsui and Satz (1986)

### Restorations of broken symmetries

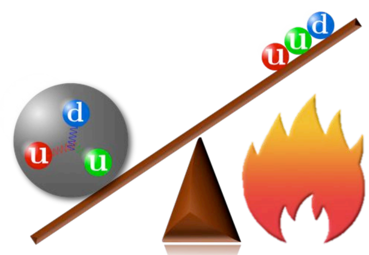
restored pattern
of **chiral** and $\mathrm{U_A(1)}$ symmetries
the nature of phase transition

Pisarski and Wilczek (1984)

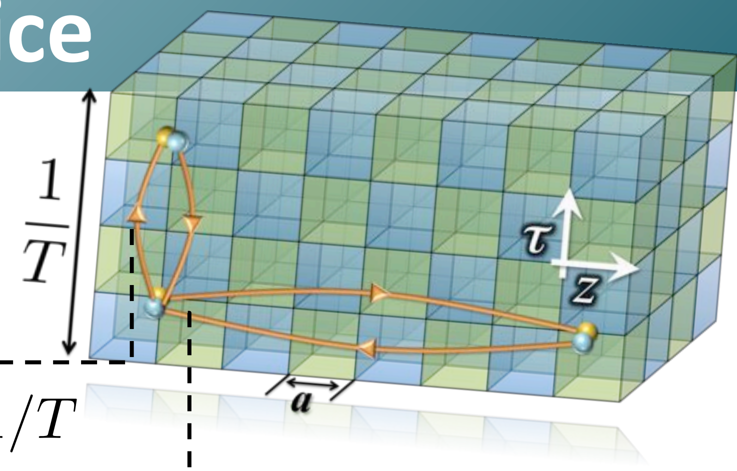


Theoretical understanding in lattice QCD simulations
from spatial correlation functions

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:

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

$M(T)$: screening mass

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

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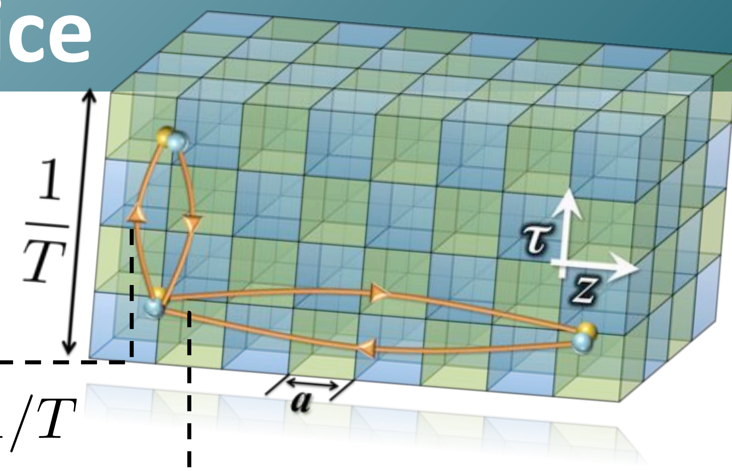


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## Spectral function

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

e.g.) reconstruction of σ: MEM

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

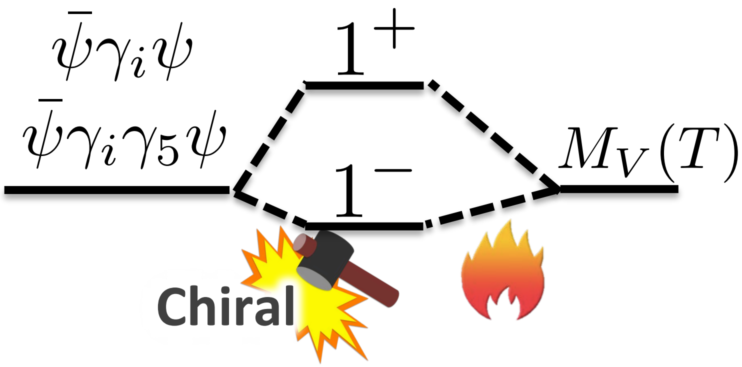
No $T$ dependence in Kernel: direct probe of thermal modification of σ

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

# Hadronic excitation on Lattice

## Parity partner of meson states

**Vector** (vector and axial-vector)

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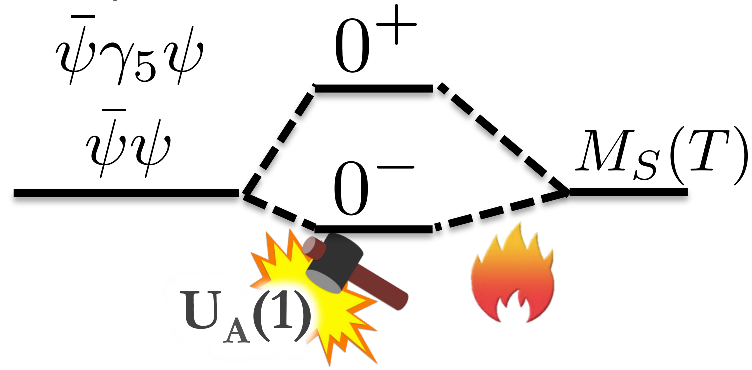


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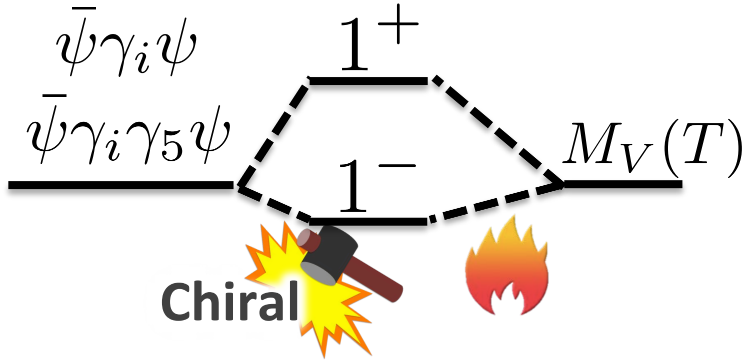


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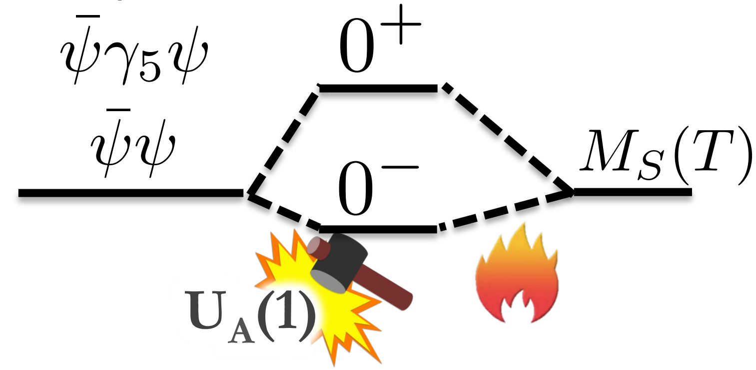


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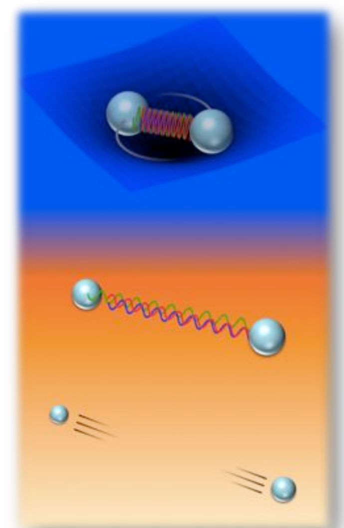
## Behavior in limiting cases:

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

<u>Lattice parameters</u>

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

## Mesons contents

| $\Gamma$ | $J^P$ | $u\bar{d}$ | $u\bar{s}$ | $u\bar{c}$ | $s\bar{s}$ | $s\bar{c}$ | $c\bar{c}$ |
|---|---|---|---|---|---|---|---|
| $\gamma_5$ | $0^-$ | $\pi$ | $K$ | $D$ | $(\eta_{s\bar{s}})$ | $D_s$ | $\eta_c$ |
| $1$ | $0^+$ | – | $K_0^*$ | $D_0^*$ | – | $D_{s0}^*$ | $\chi_{c0}$ |
| $\gamma_i$ | $1^-$ | $\rho$ | $K^*$ | $D^*$ | $\phi$ | $D_s^*$ | $J/\psi$ |
| $\gamma_i\gamma_5$ | $1^+$ | – | $K_1$ | $D_1$ | $f_1(1420)$ | $D_{s1}$ | $\chi_{c1}$ |

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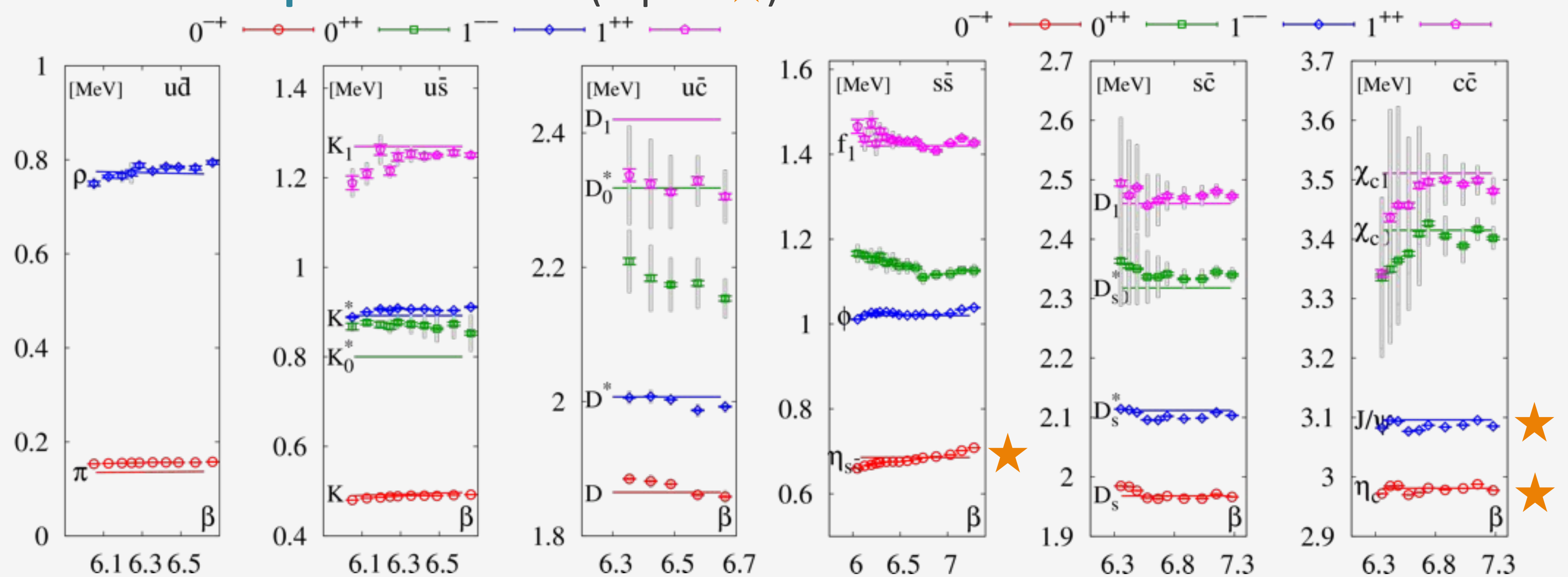
## Meson spectra at T = 0 (input: ★)



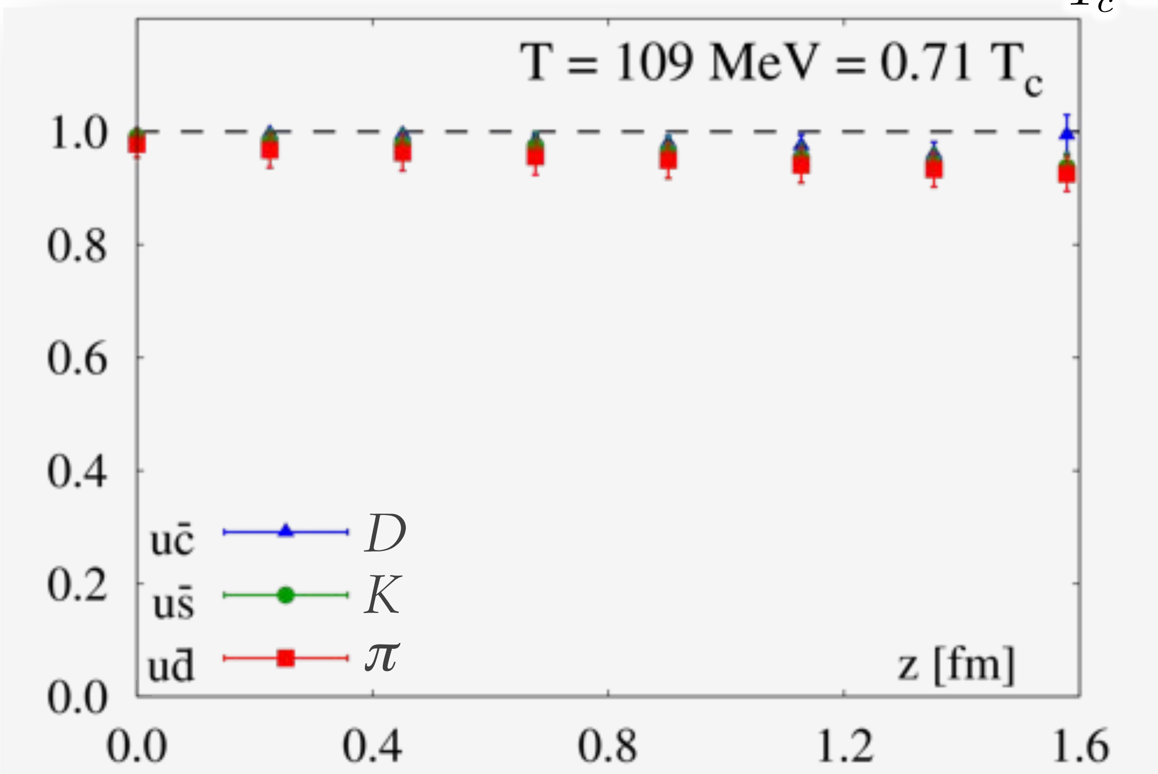
# Ratio of spatial correlation functions

## 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 $\sigma$

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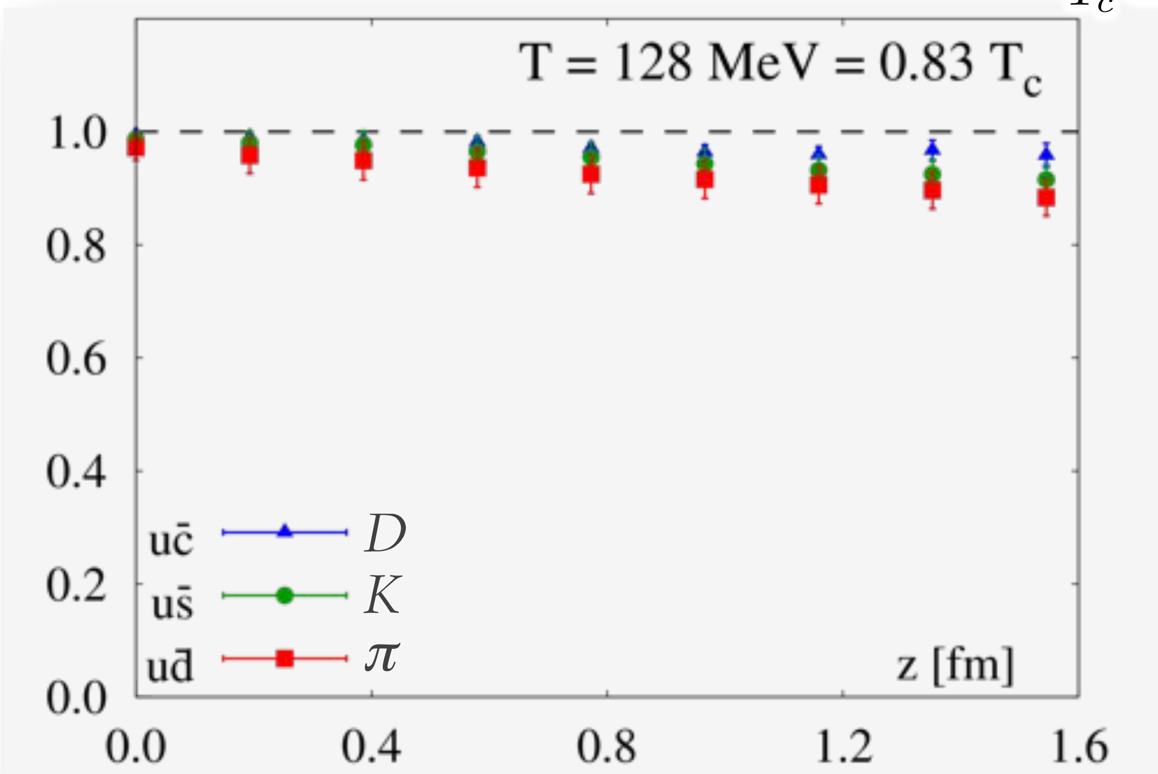


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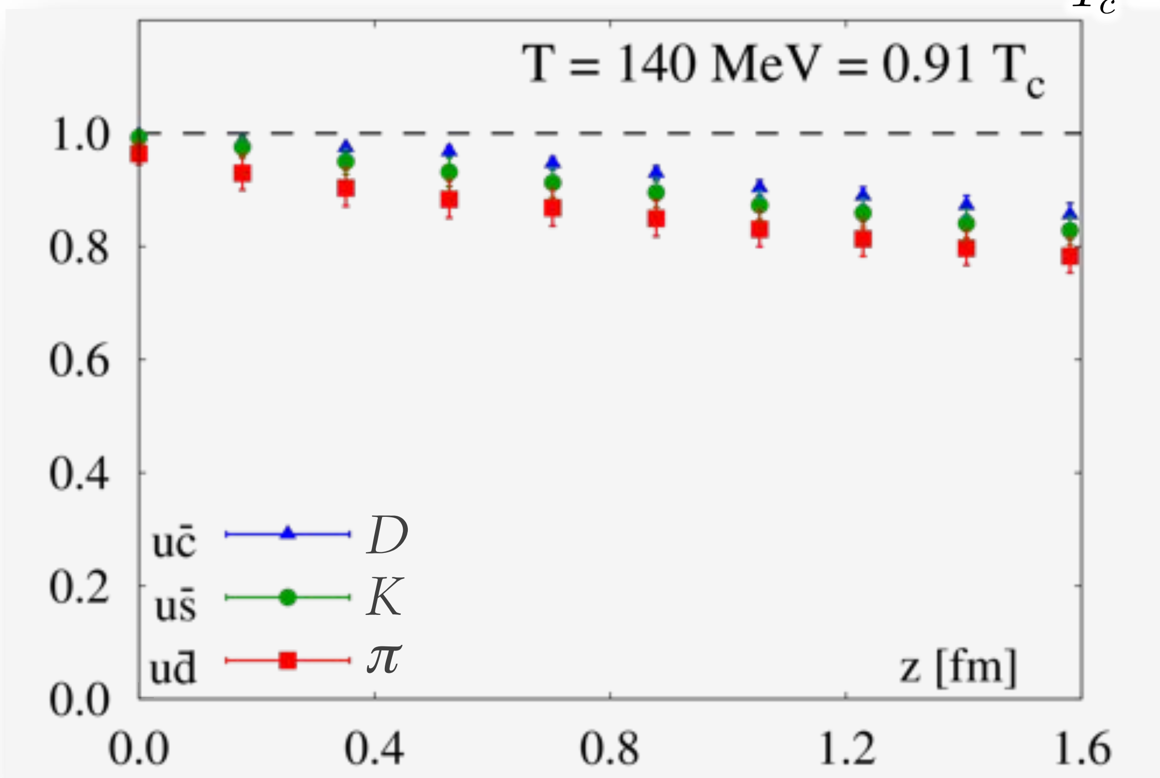


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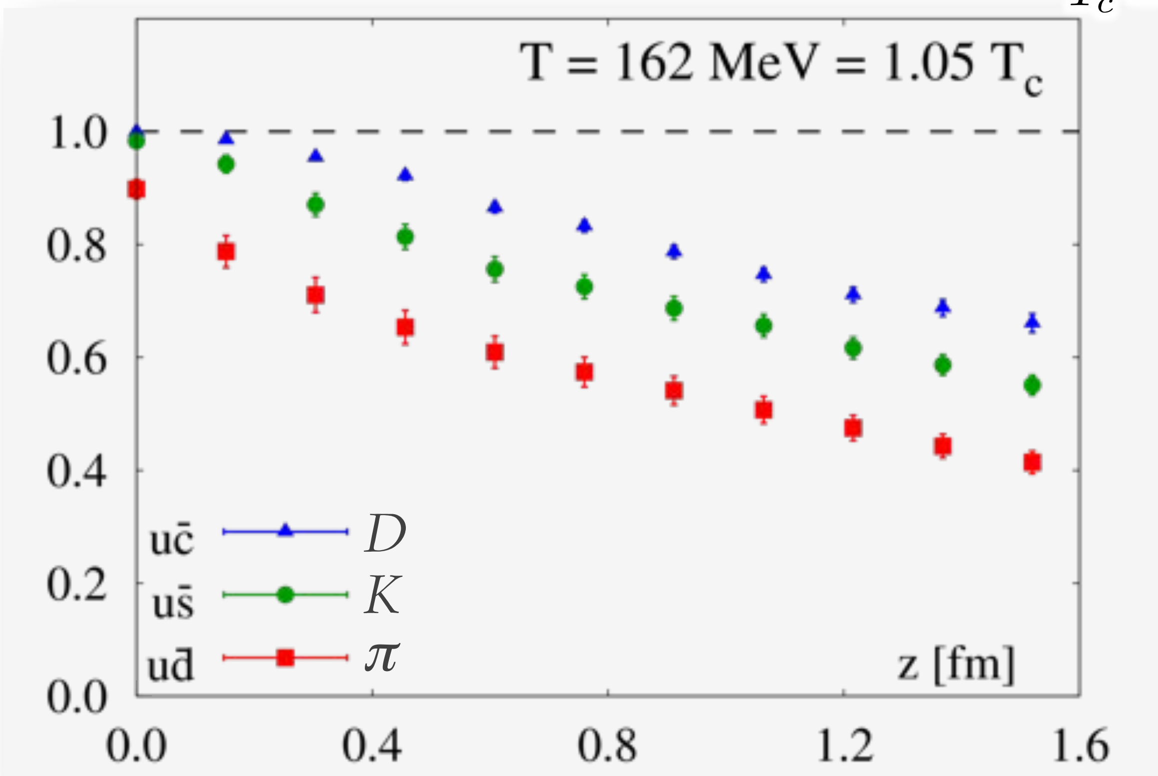


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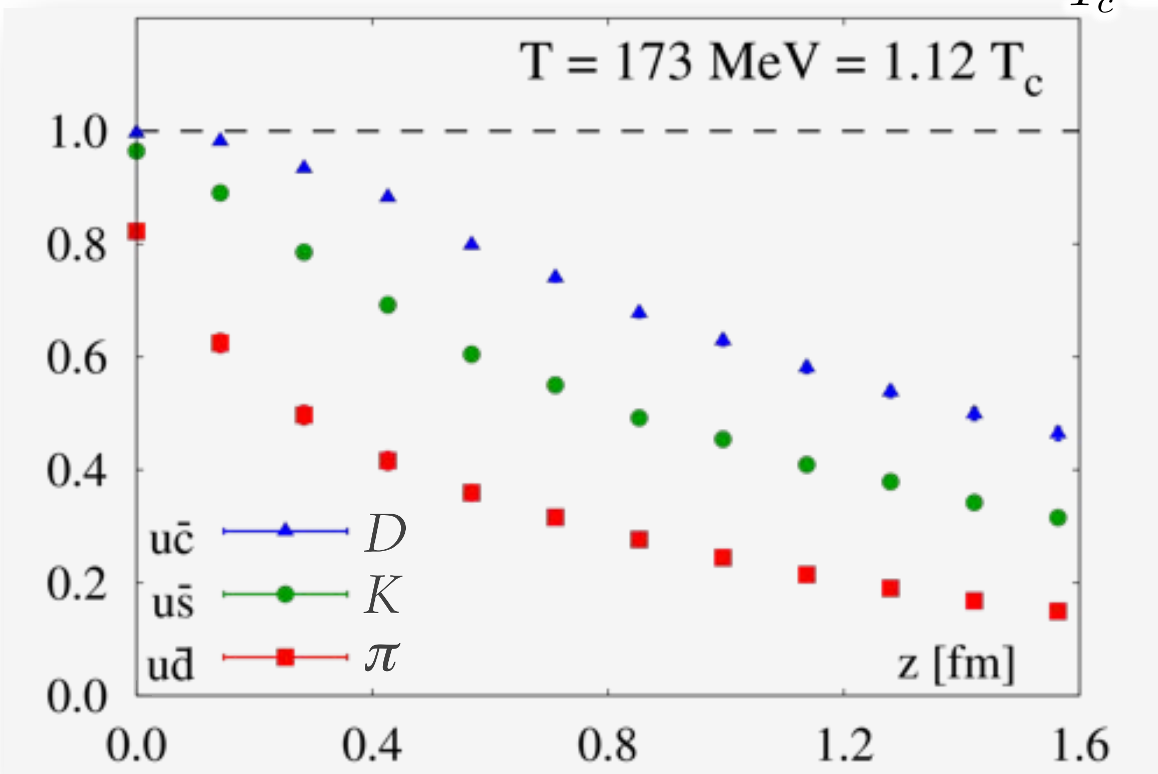


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# Mass difference

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

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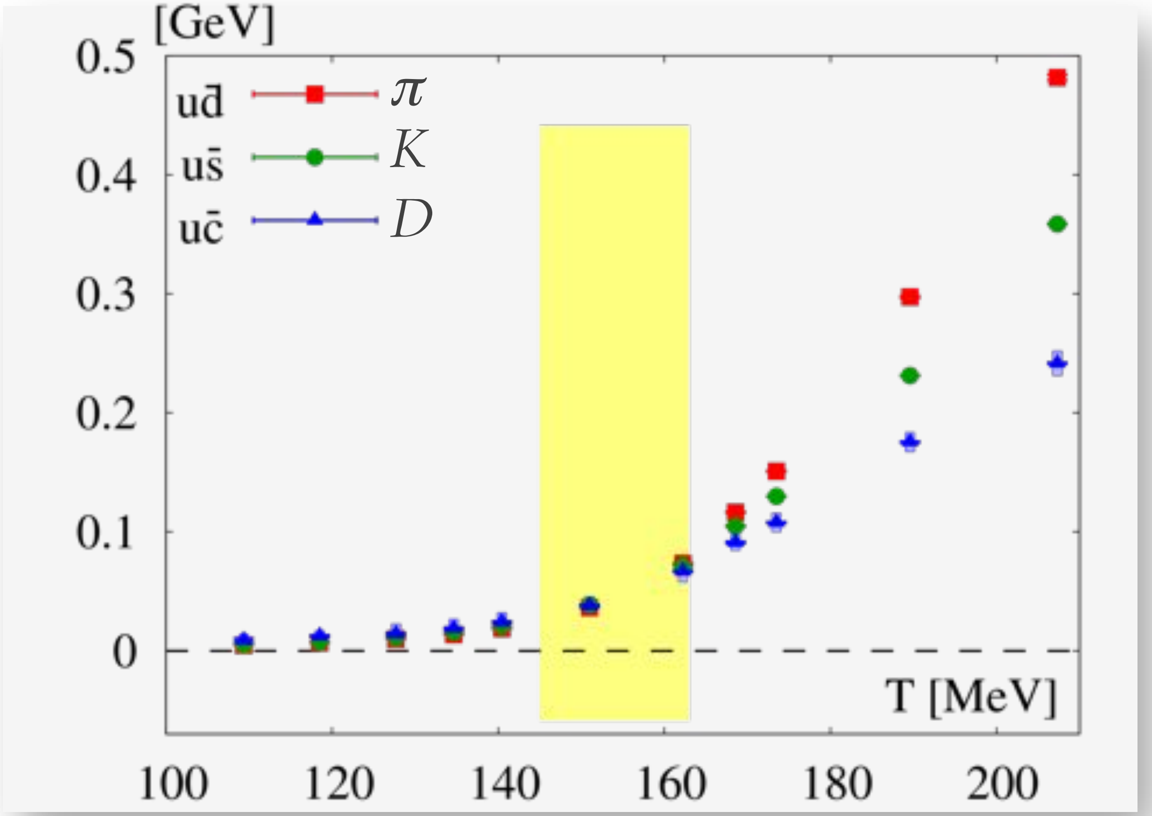


- $u\bar{d},\ u\bar{s},\ u\bar{c}$ : explicit thermal modification below $T_c$,

  similar modification pattern at $T < T_c$,
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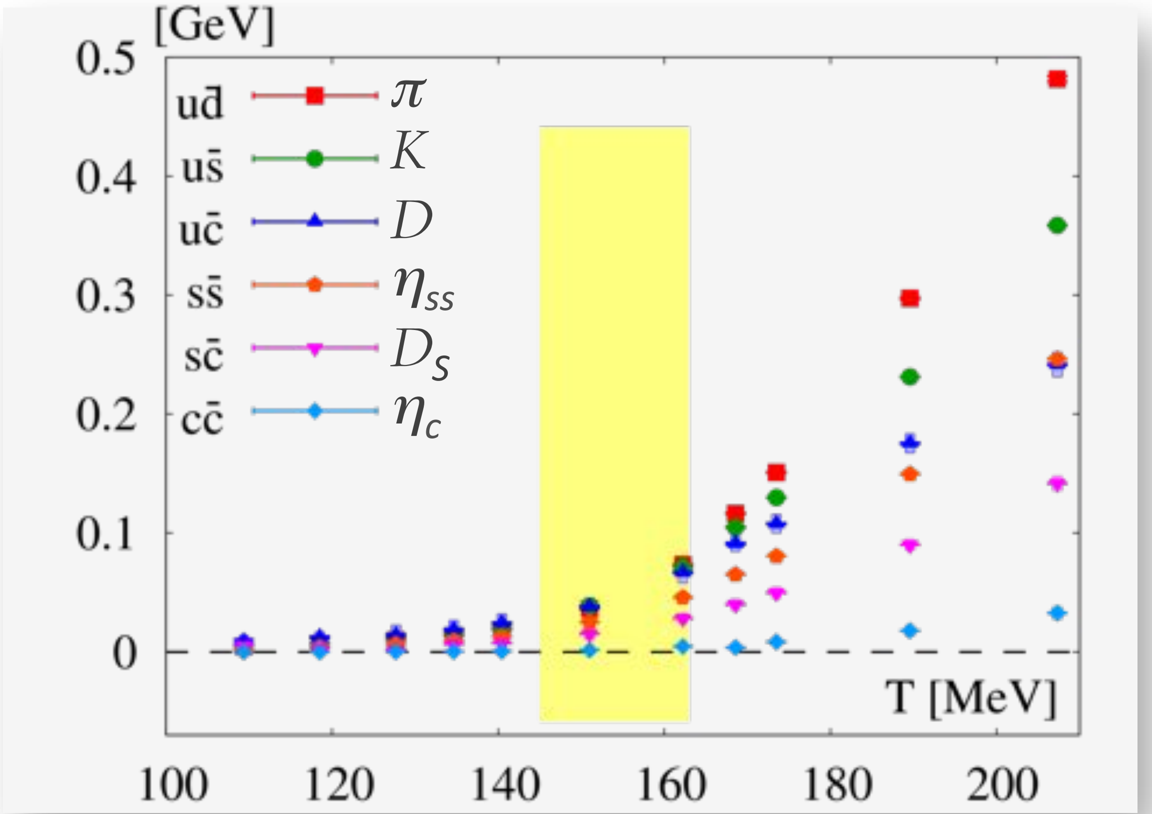


- $u\bar{d},\ u\bar{s},\ u\bar{c}$ : explicit thermal modification below $T_c$,
  - similar modification pattern at $T < T_c$,
  - explicit flavor dependence at $T > T_c$
- $s\bar{s},\ s\bar{c}$ : slight modification below $T_c$
- $c\bar{c}$ : stable beyond $T_c$

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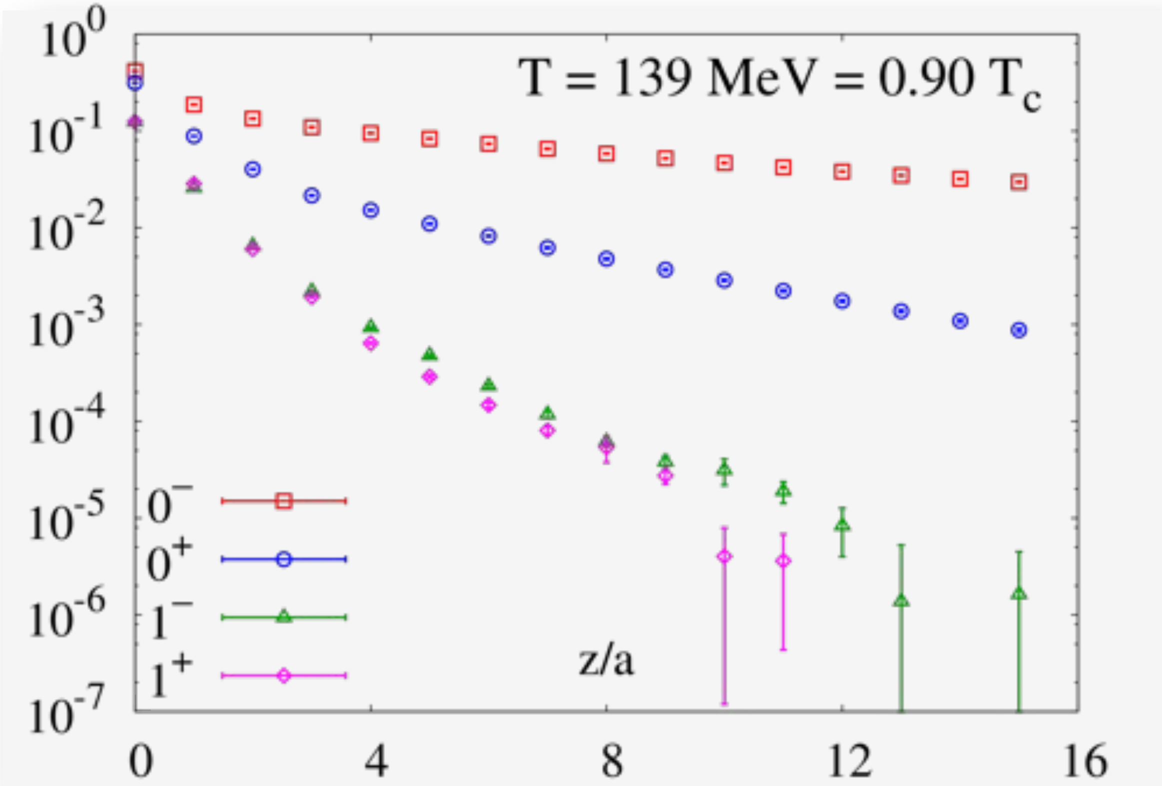
# Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

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

$$G^S(z,T)$$



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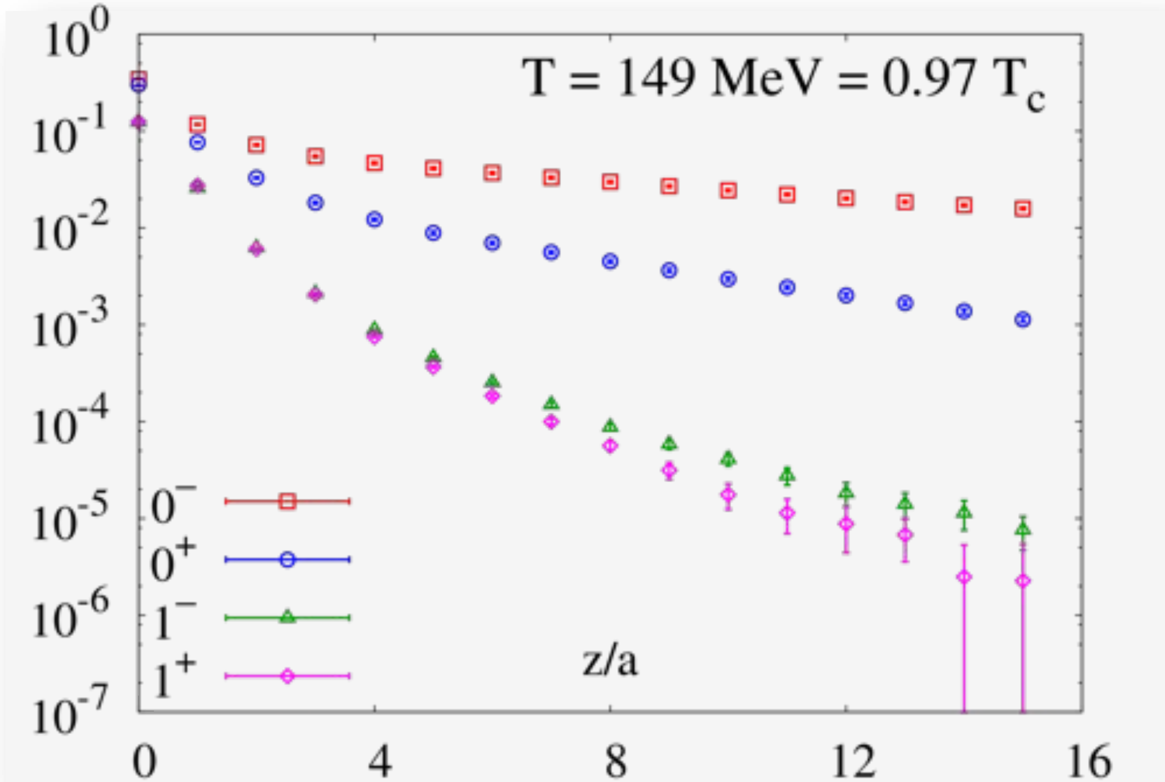

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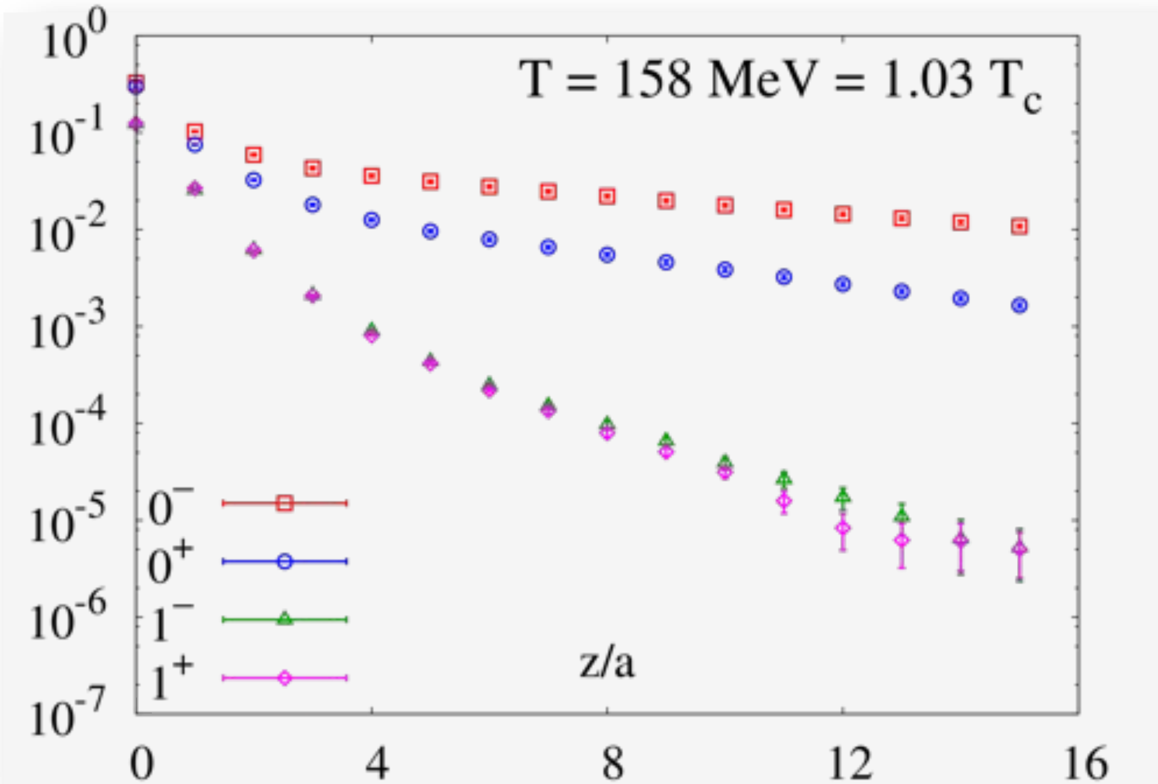


- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$

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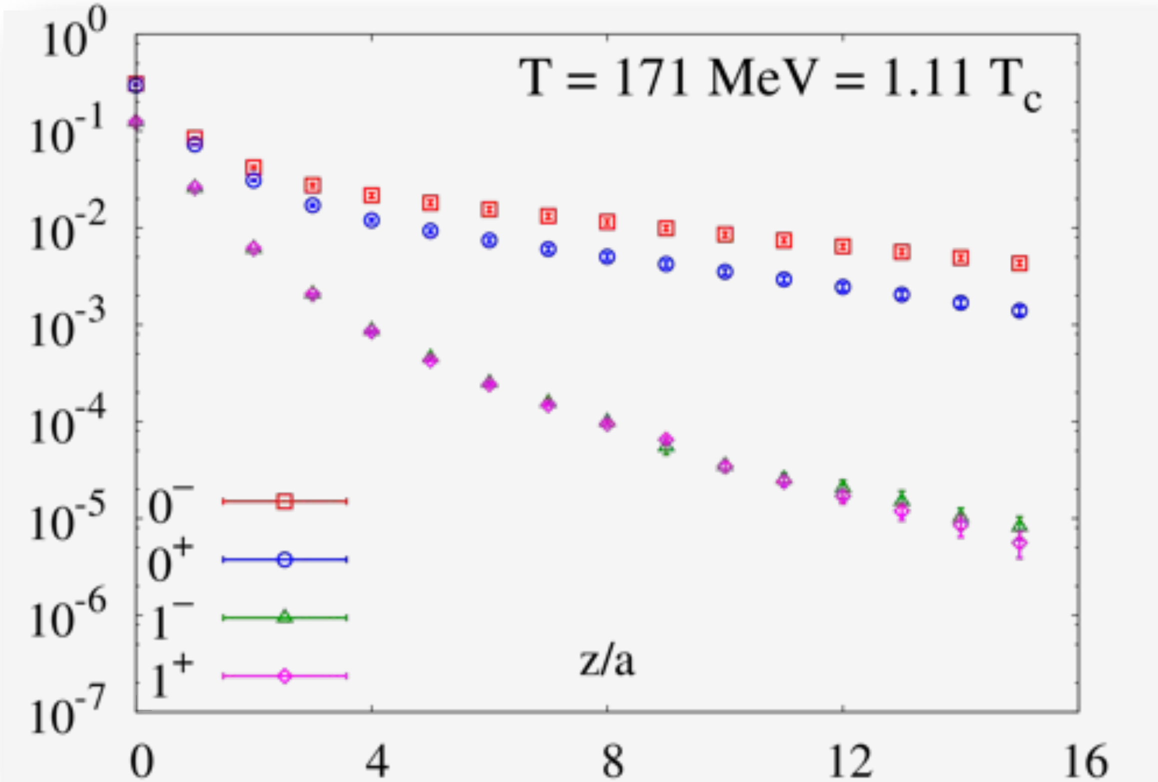


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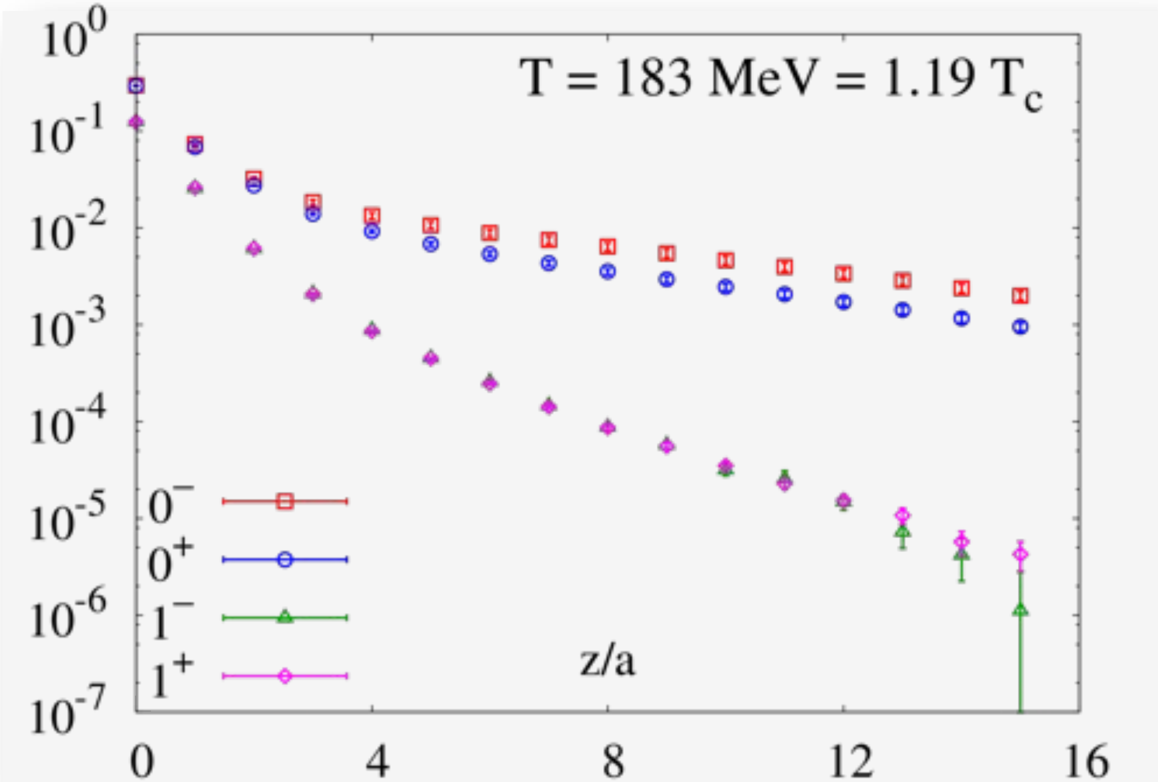


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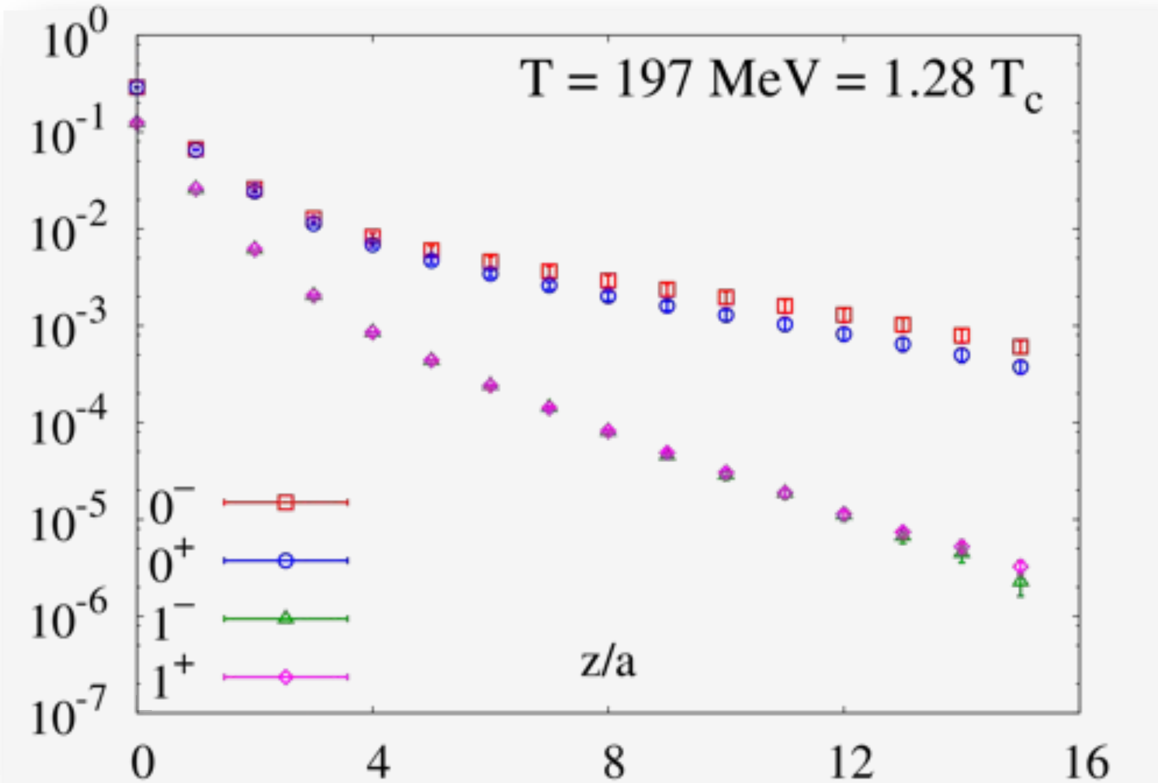


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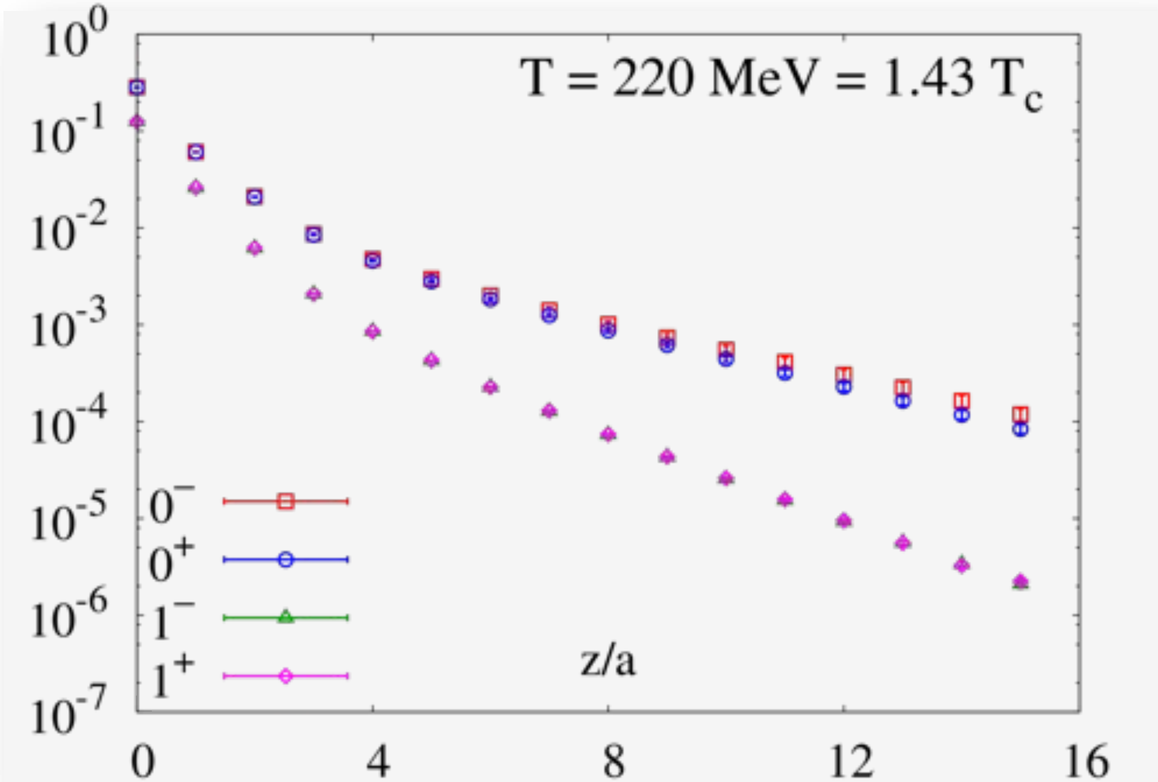


- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$
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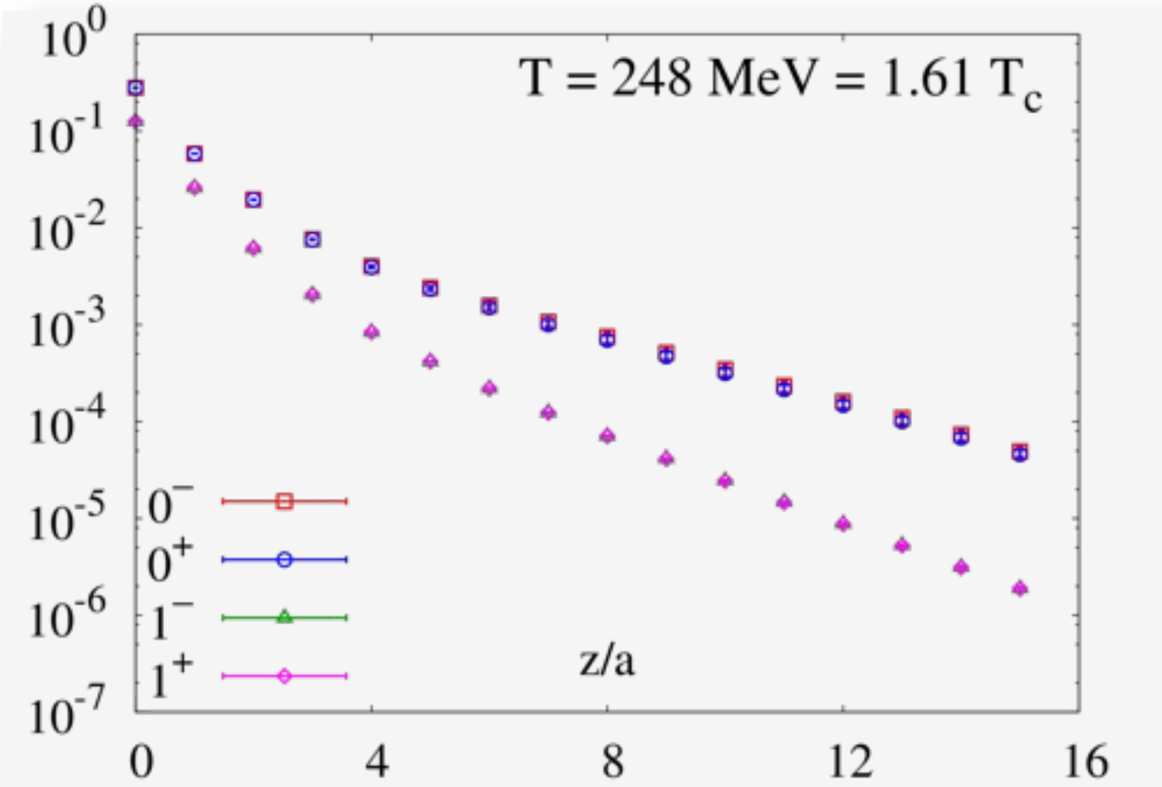


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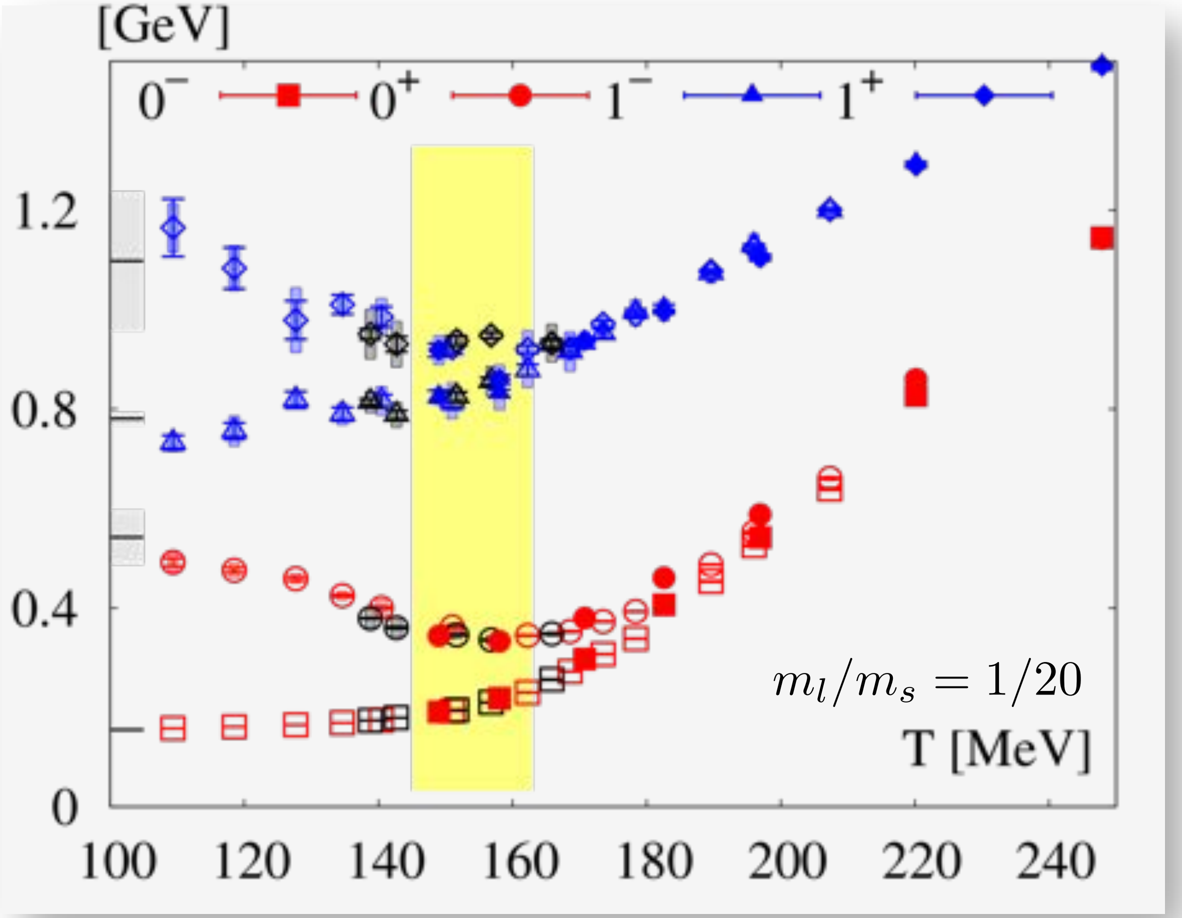
# Restoration of broken symmetries

**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: $N\tau = 12$

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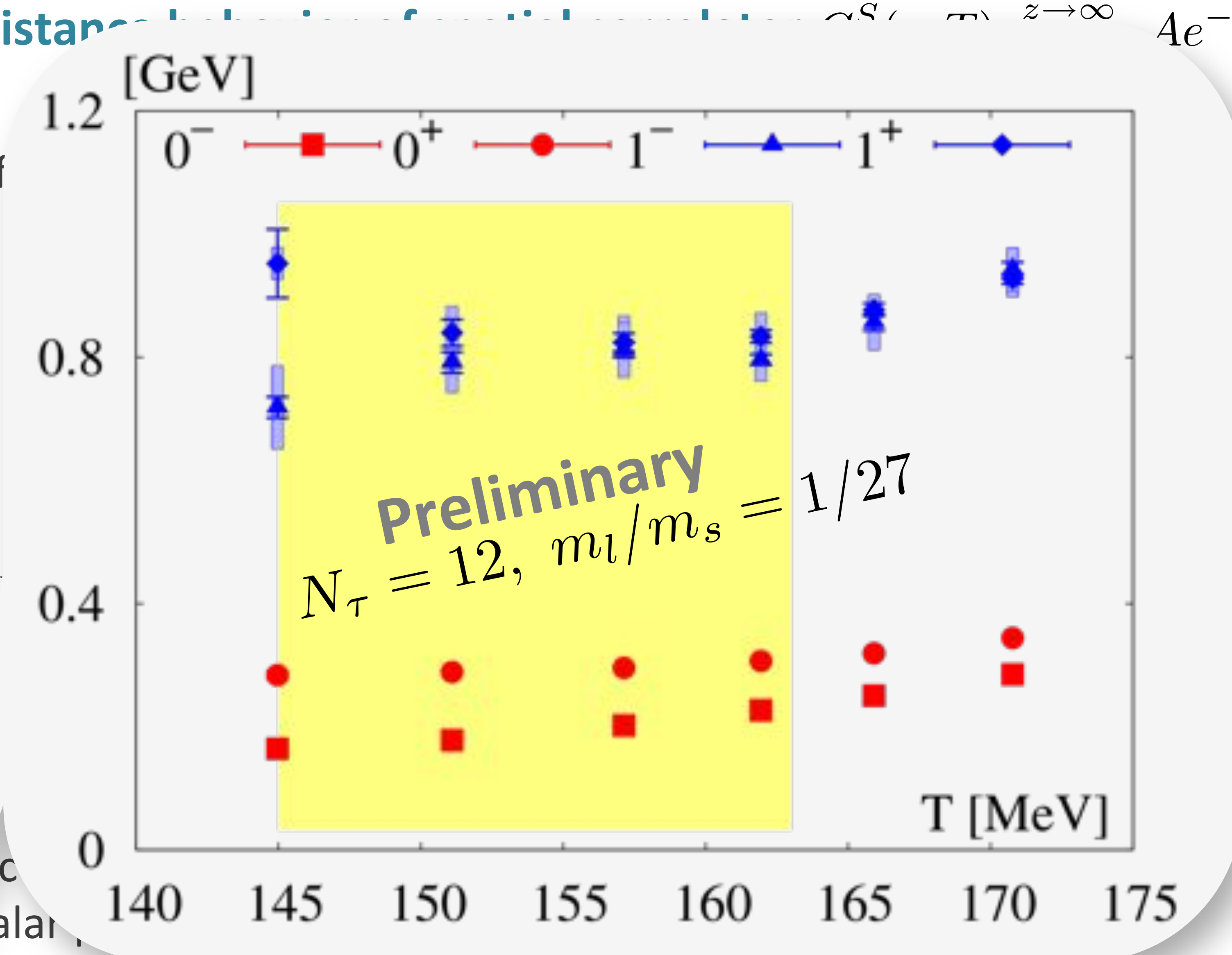
➡ chiral: restored, $U_A(1)$: broken at $T_c$, no dependence on lattice spacing

# Restoration of broken symmetries

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

Light-unf…

Open: …
Black: …
Filled: …




- Vec…
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# Summary

## In-medium mesons from spatial correlation function

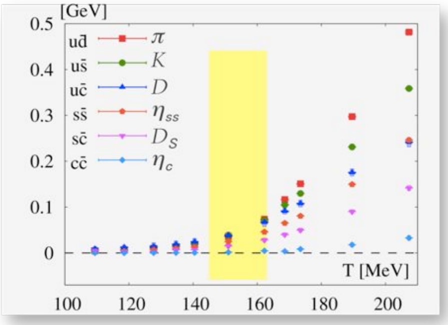
➡ Sensitive to thermal effect at finite $T$ on lattice

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

<u>Thermal modification of mesons</u>

- $u\bar{d},\ u\bar{s},\ u\bar{c}$ : explicitly modified below $T_c$,

  ➡ similar below $T_c$,
  flavor dependence above $T_c$




- $s\bar{s},\ s\bar{c}$ : slightly modified below $T_c$
- $c\bar{c}$ : stable beyond $T_c$ PRD91 (2015) 5, 054503

<u>Restoration of broken symmetries</u>

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➡ in continuum and physical quark mass (preliminary)