格子QCDによる
空間相関から迫る
中間子熱変化と壊れた対称性の回復

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in collaboration with

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熱場の量子論とその応用、2015年8月31日--9月2日

Introduction

Thermal fluctuation in QCD

Modifications of hadrons

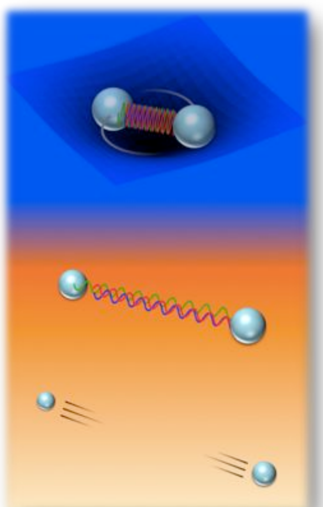
sequential melting pattern
of **quarkonium** and
open-flavor mesons
e.g. J/ψ suppression

Matsui and Satz (1986)

Restorations of broken symmetries

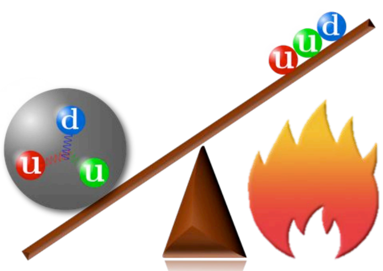
restored pattern
of **chiral** and $U_A(1)$ symmetries
the nature of phase transition

Pisarski and Wilczek (1984)

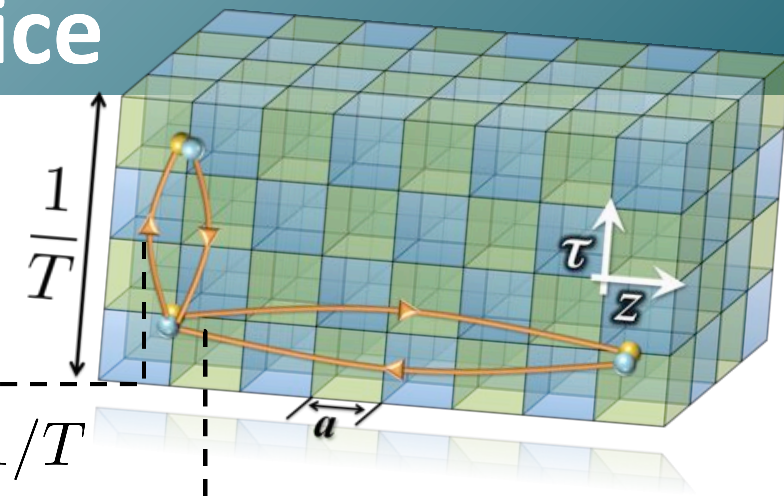


Theoretical understanding in lattice QCD simulations
from spatial correlation functions

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



Hadronic excitation on Lattice



Temporal correlation function:

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

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

Spatial correlation function:

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

$M(T)$: screening mass

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

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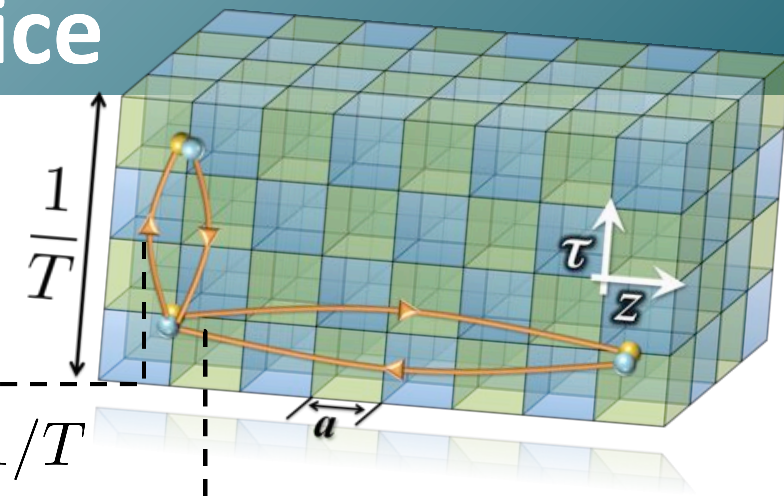

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Spectral function

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

e.g.) reconstruction of σ: MEM

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

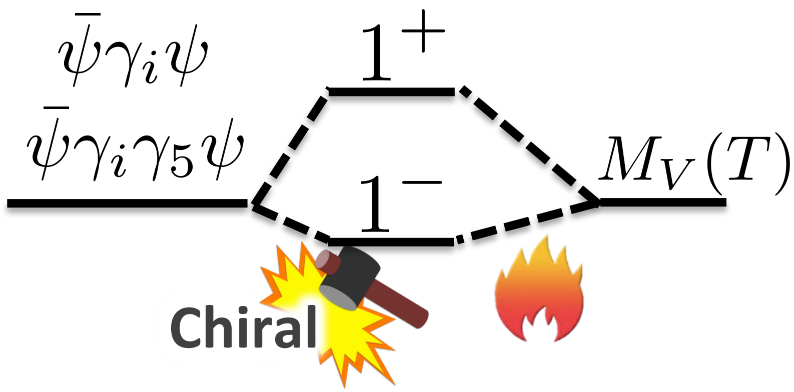
No T dependence in Kernel: direct probe of thermal modification of σ

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

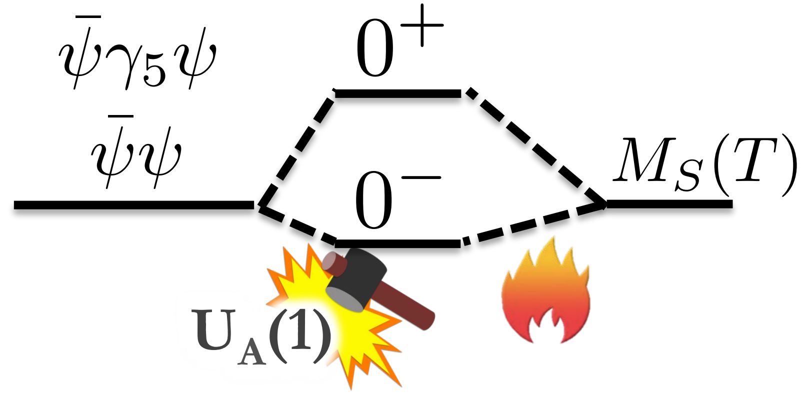
Hadronic excitation on Lattice

Parity partner of meson states

Vector (vector and axial-vector)



Scalar (pseudo-scalar and scalar)



➡ Degeneracy of parity partners: indicator of symmetry restorations

Hadronic excitation on Lattice

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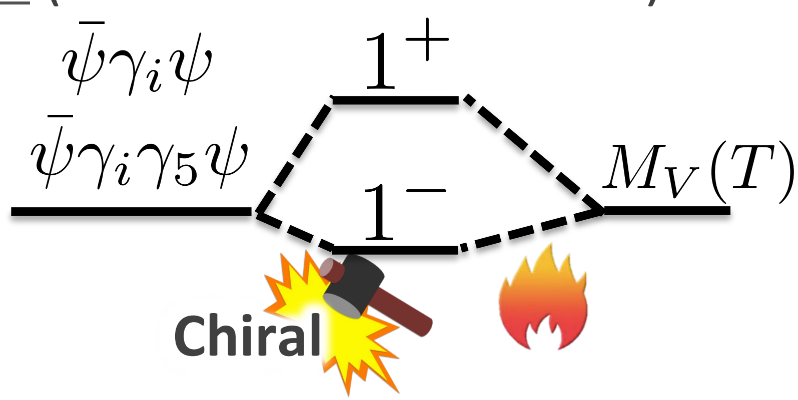

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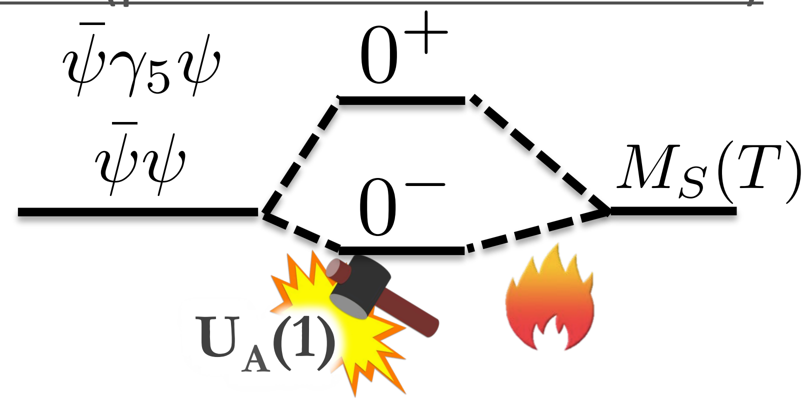


Degeneracy of parity partners: indicator of symmetry restorations

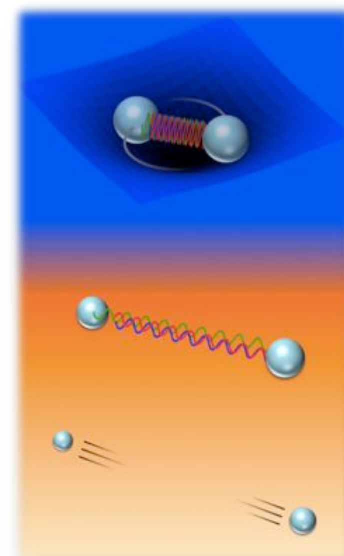
Behavior in limiting cases:

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_τ= 8 (T = 110—207 MeV)
  10 (T = 139—166 MeV)
  12 (T = 149—400 MeV)
  keeping N_s/N_τ=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}

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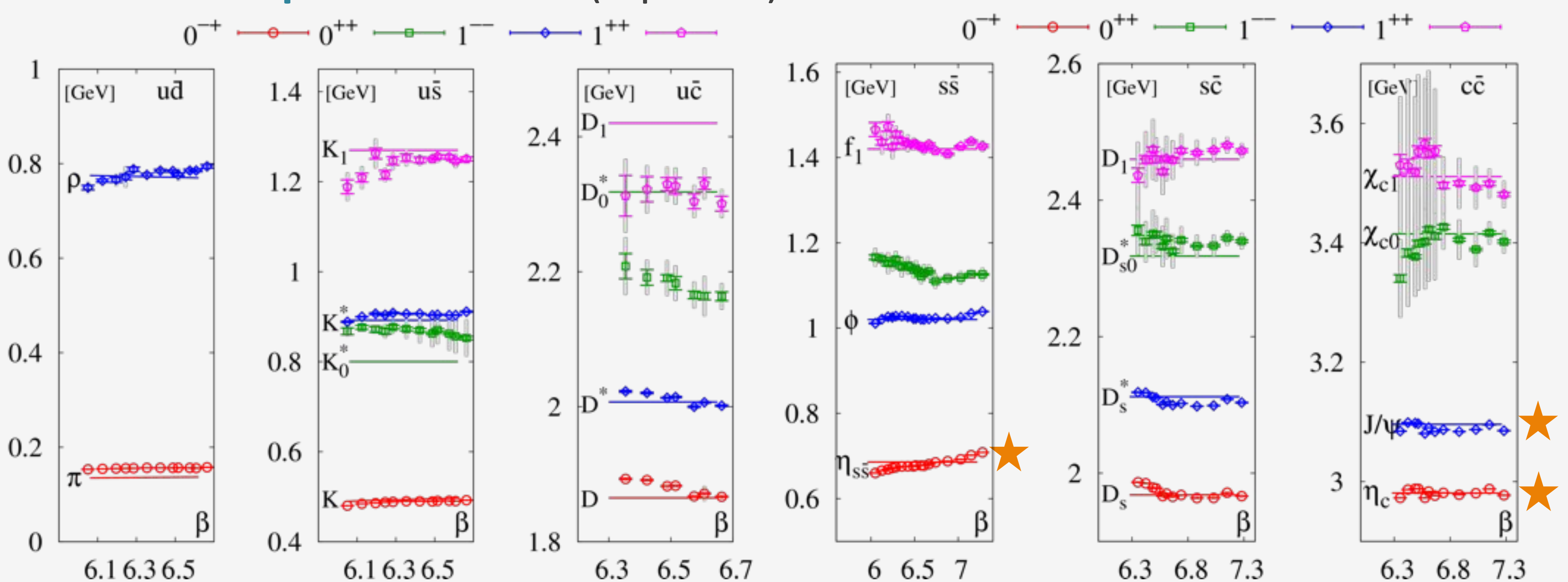
Meson spectra at T = 0 (input: ★)



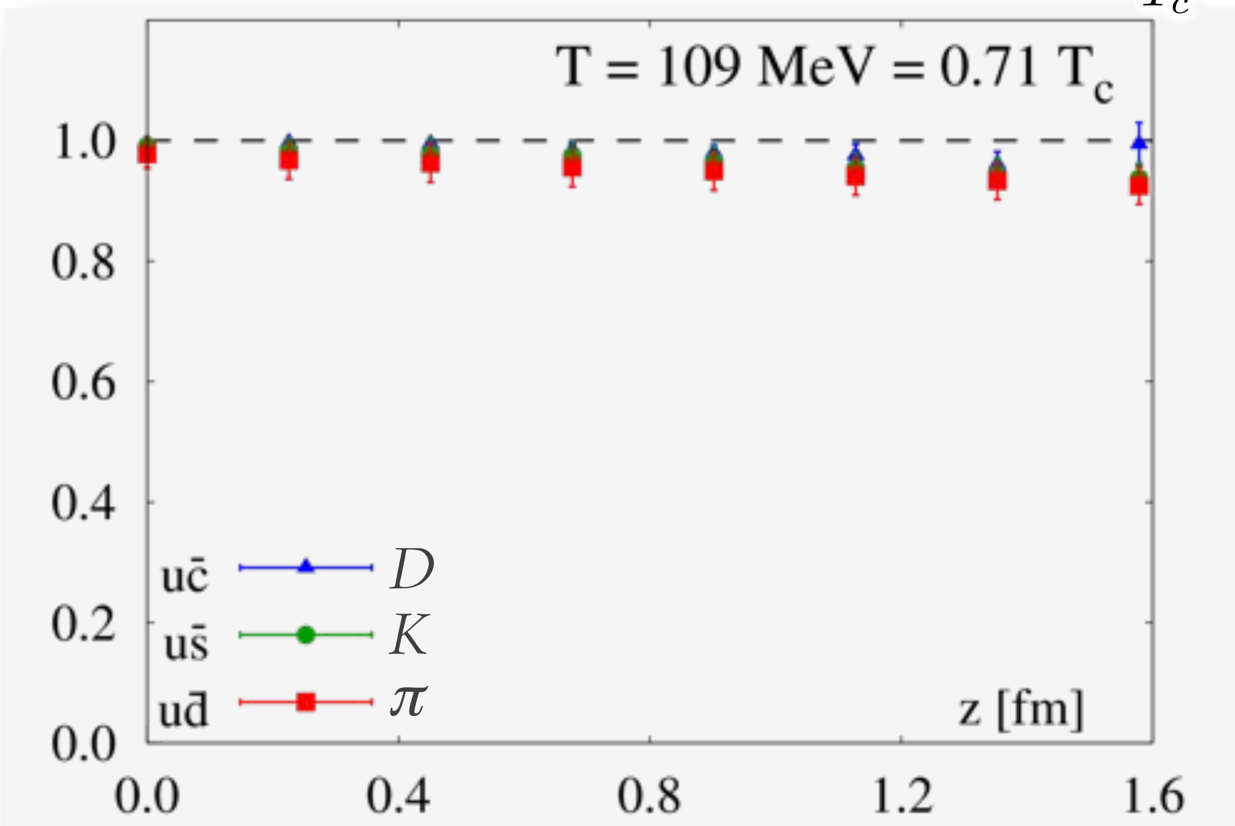
Ratio of spatial correlation functions

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 σ

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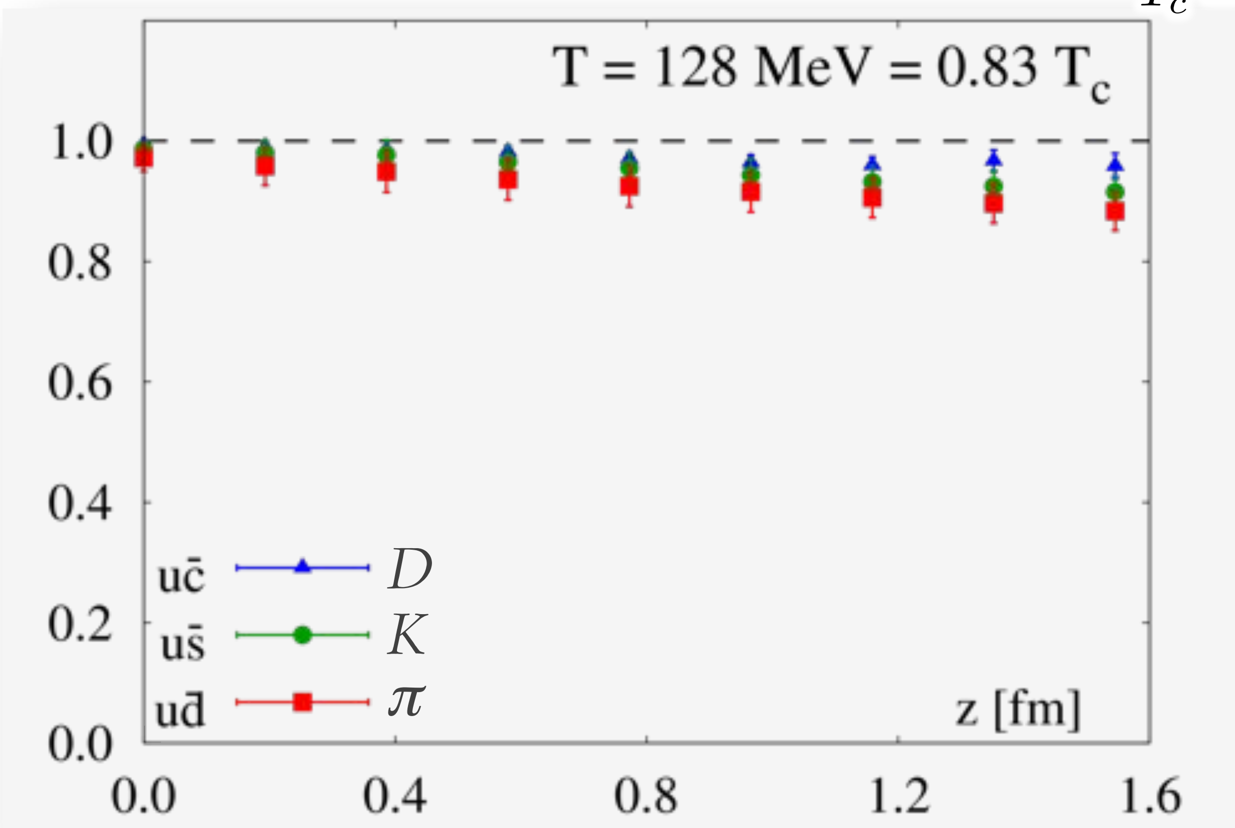

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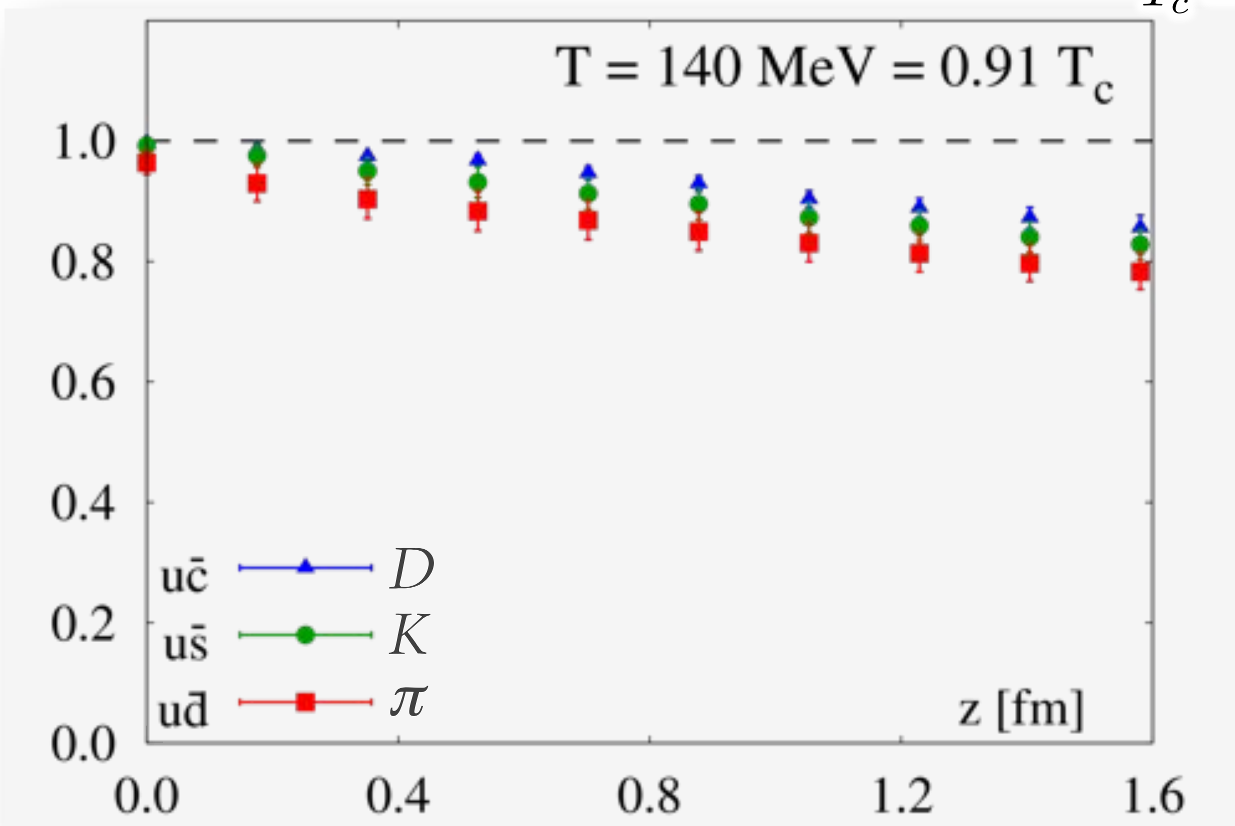

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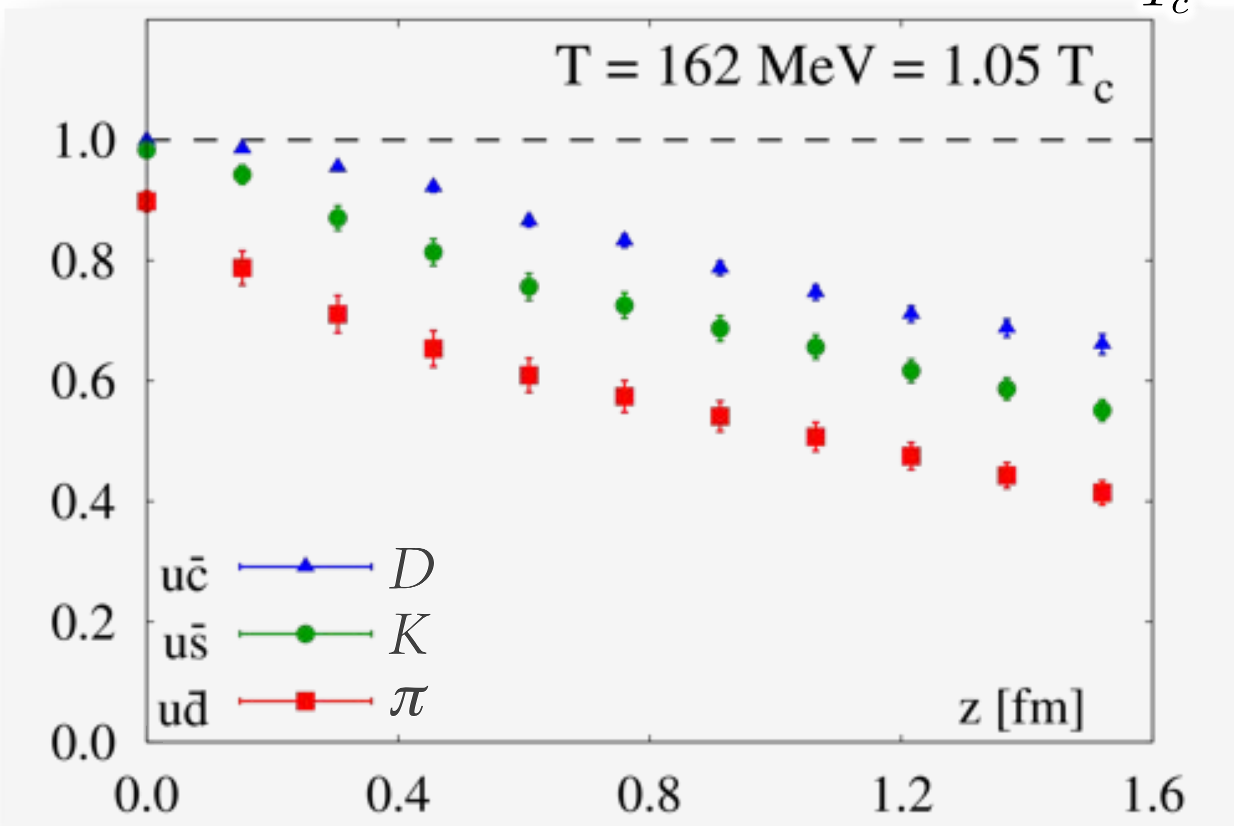

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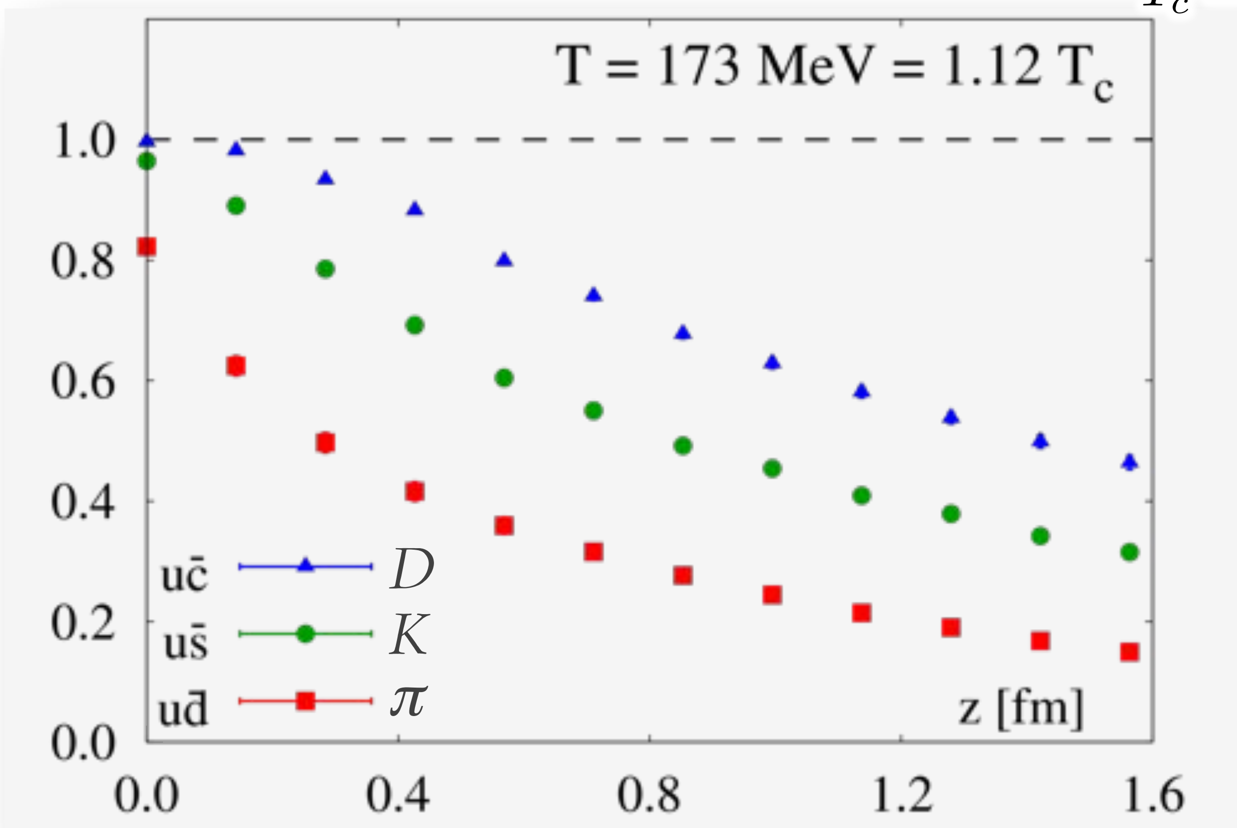

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Mass difference

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

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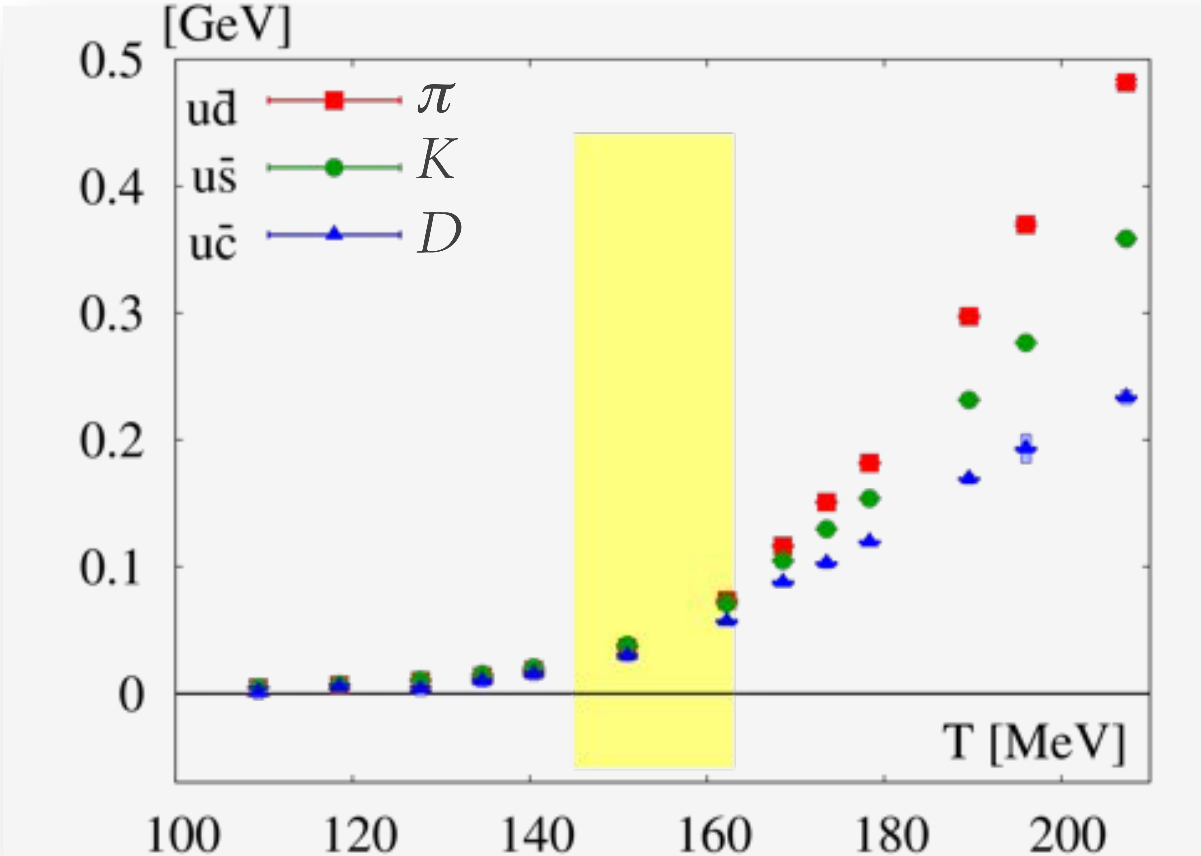

- $u\bar{d},\ u\bar{s},\ u\bar{c}$: explicit thermal modification below T_c,

similar modification pattern at $T < T_c$,
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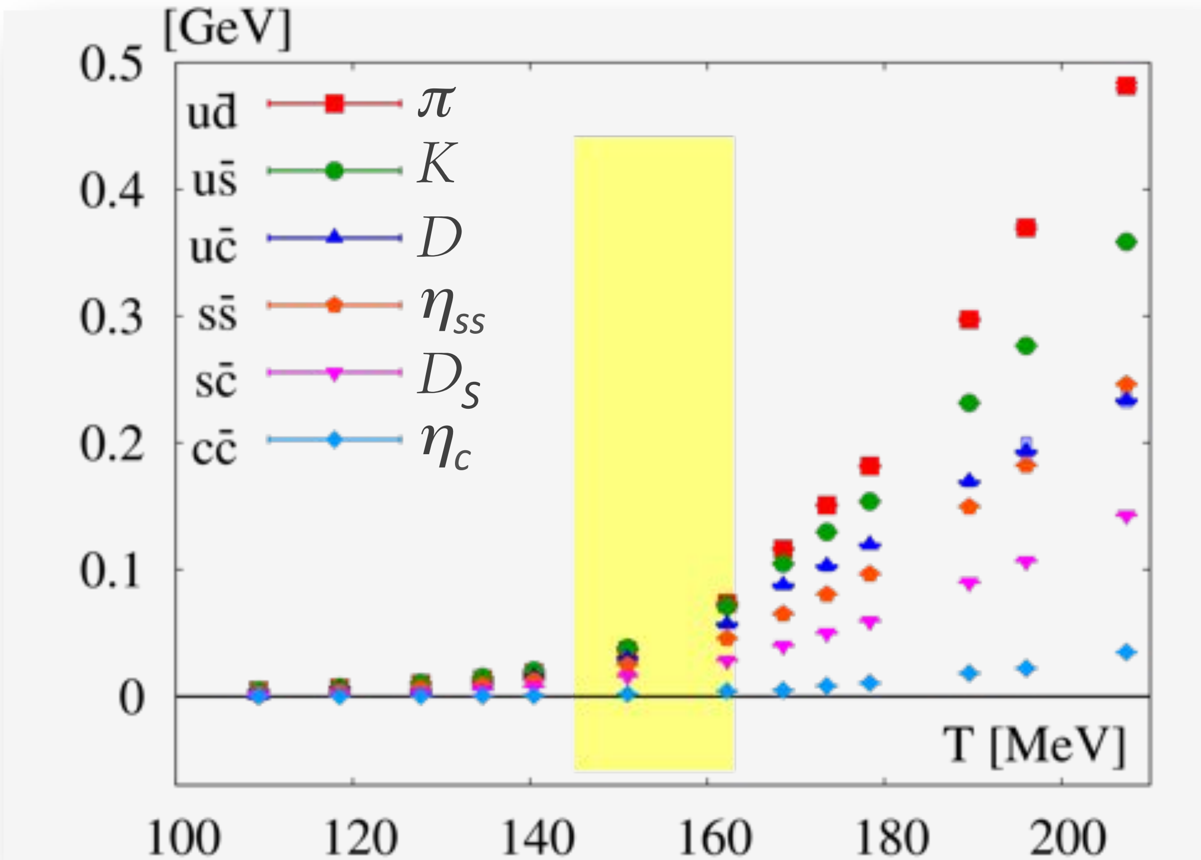

- $u\bar{d},\ \ u\bar{s},\ \ u\bar{c}$: explicit thermal modification below T_c,

  ➡ 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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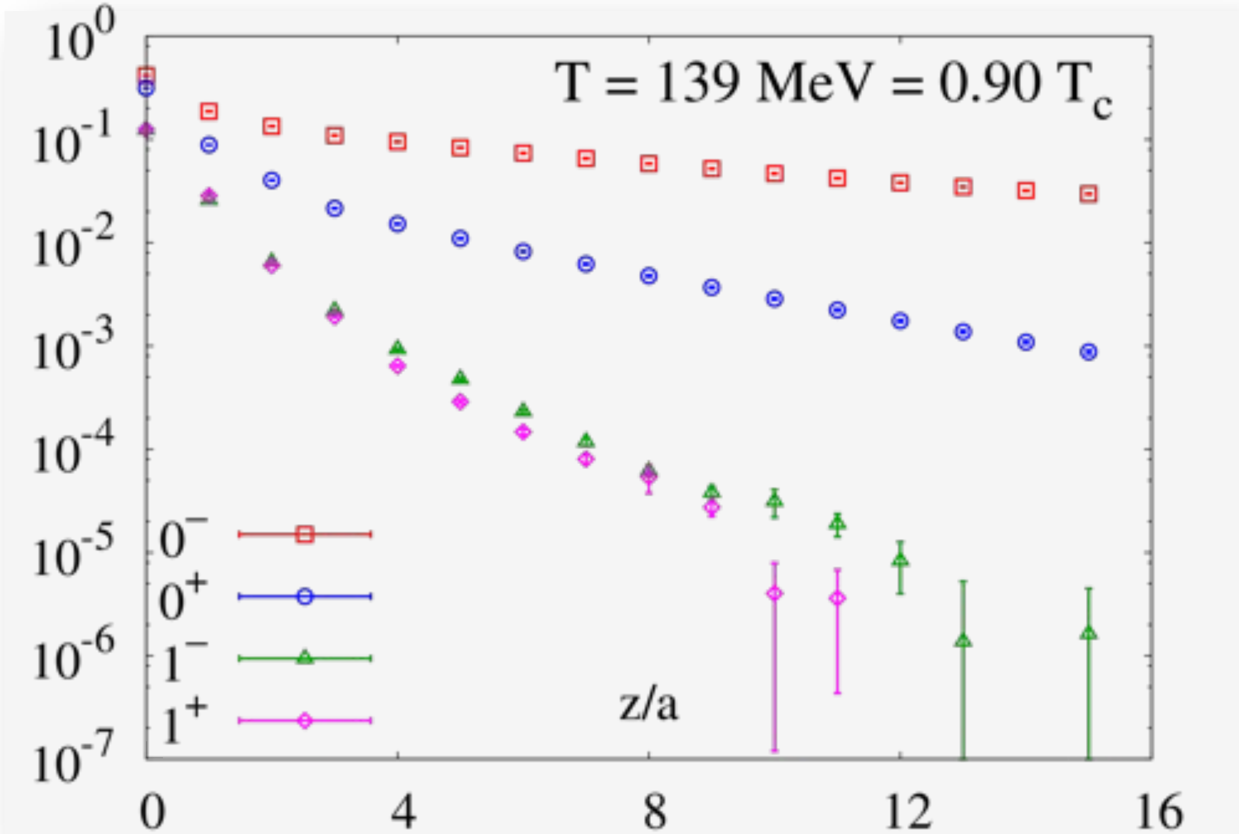
Restoration of broken symmetries

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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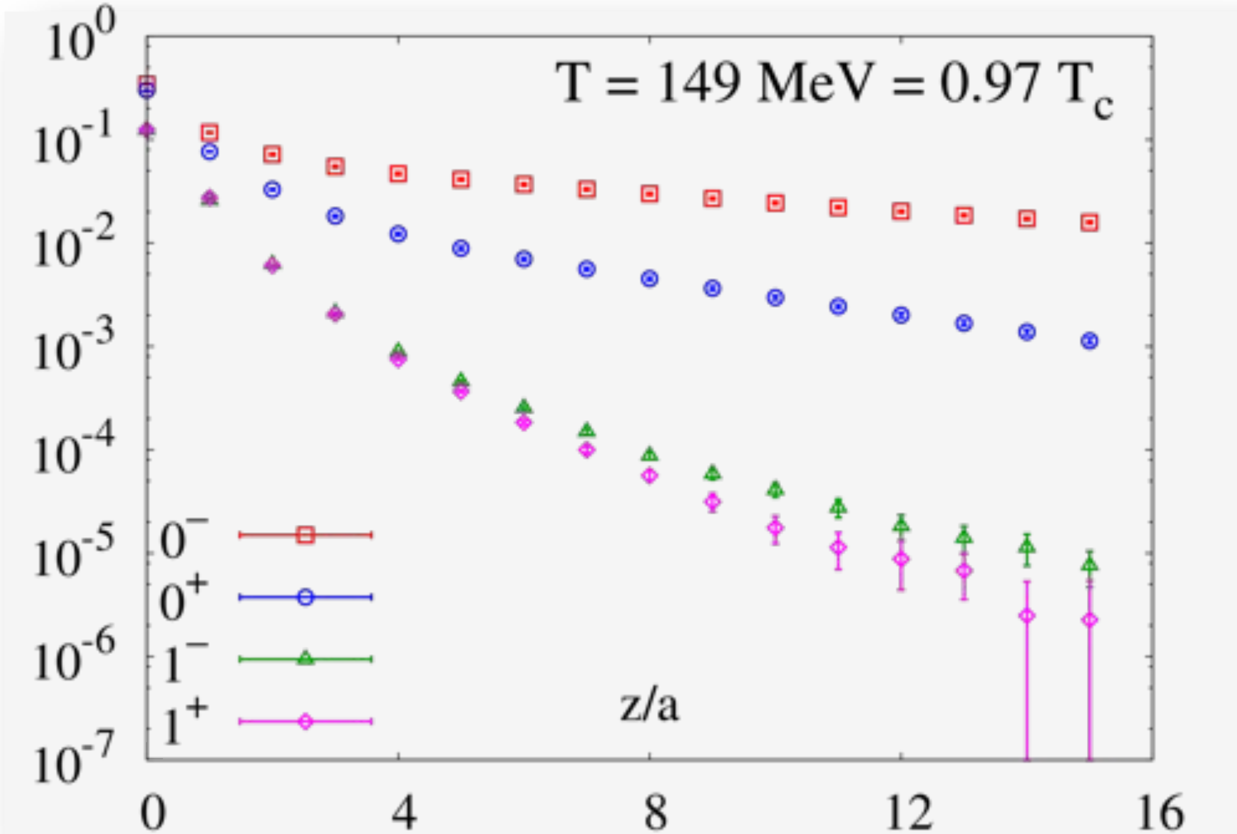

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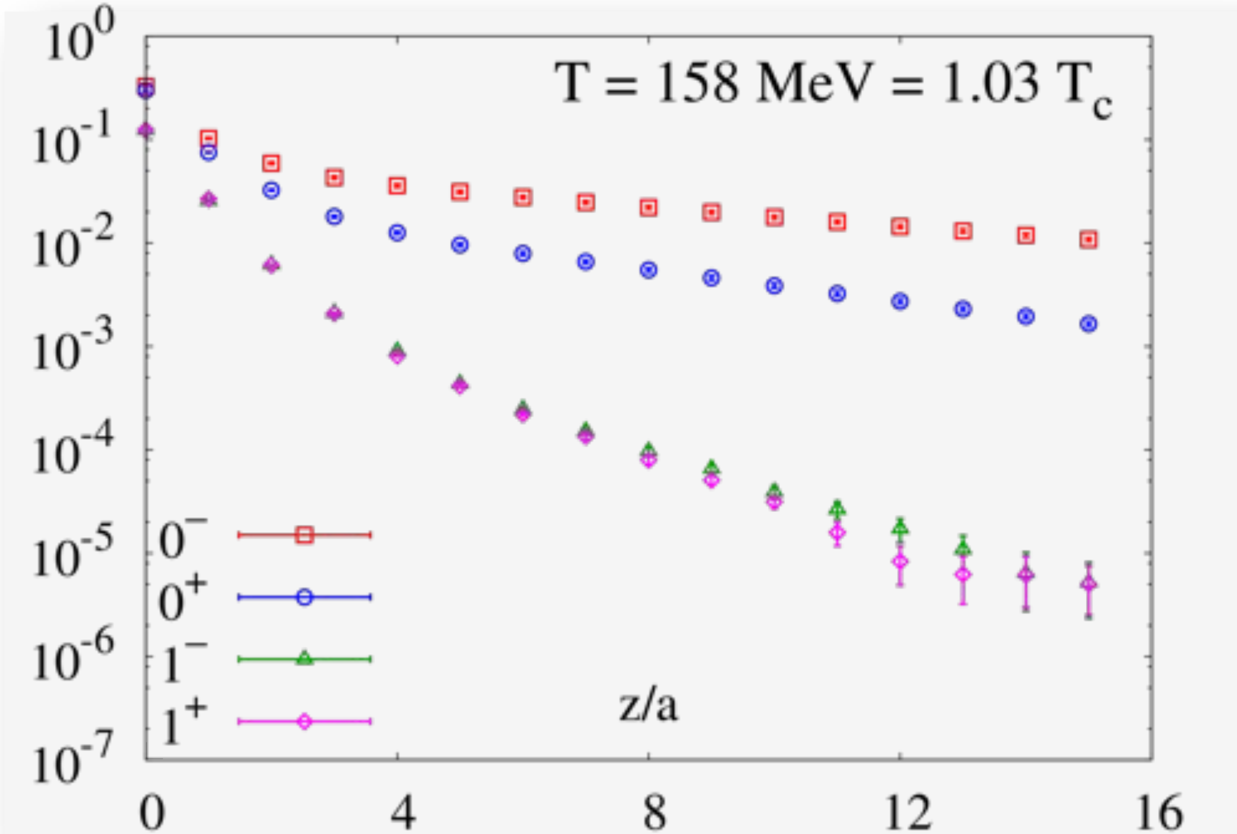

- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$

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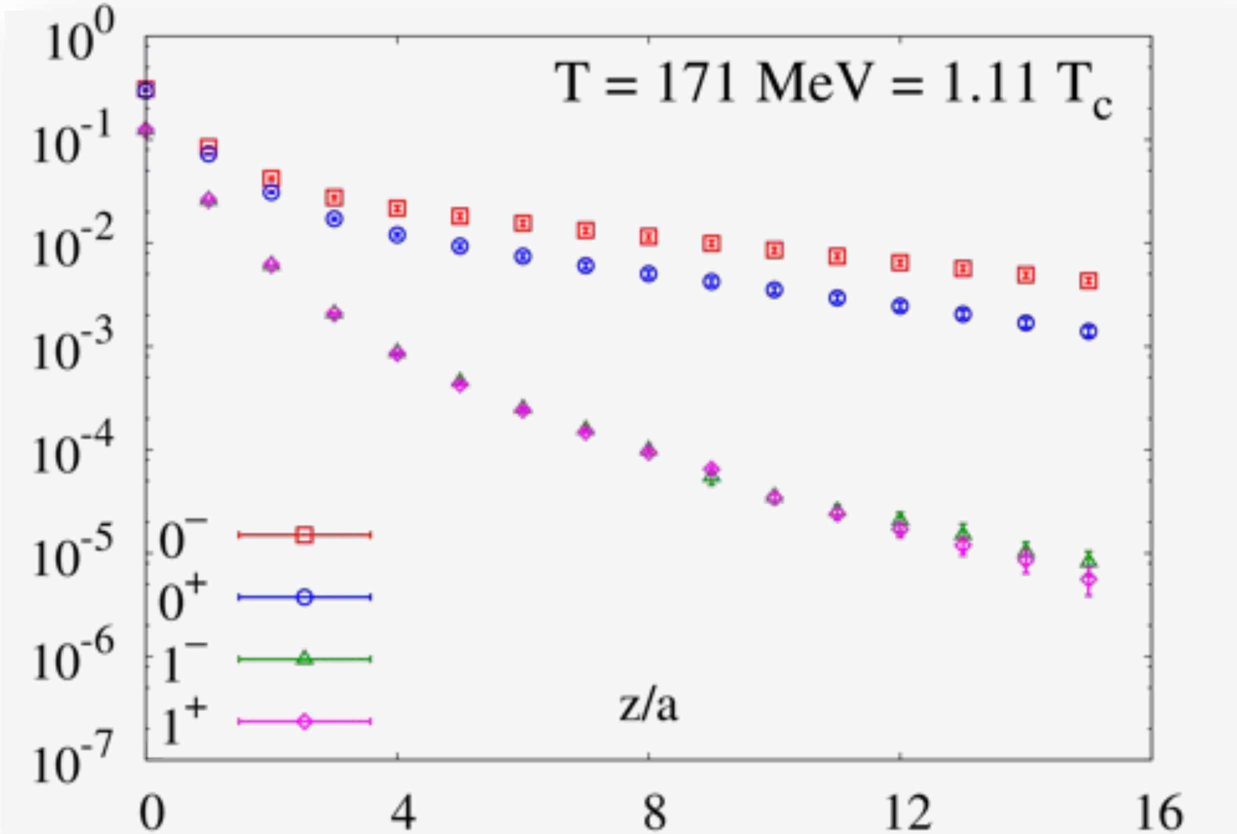

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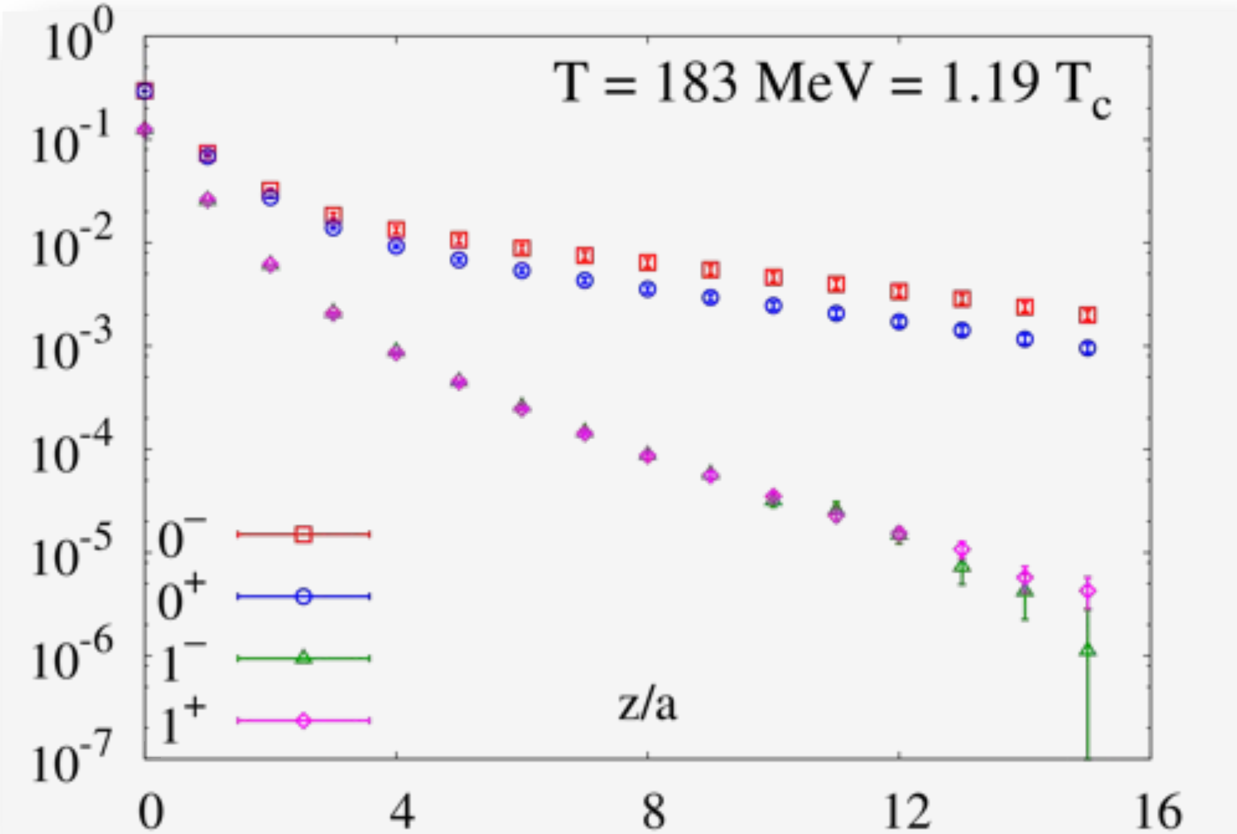

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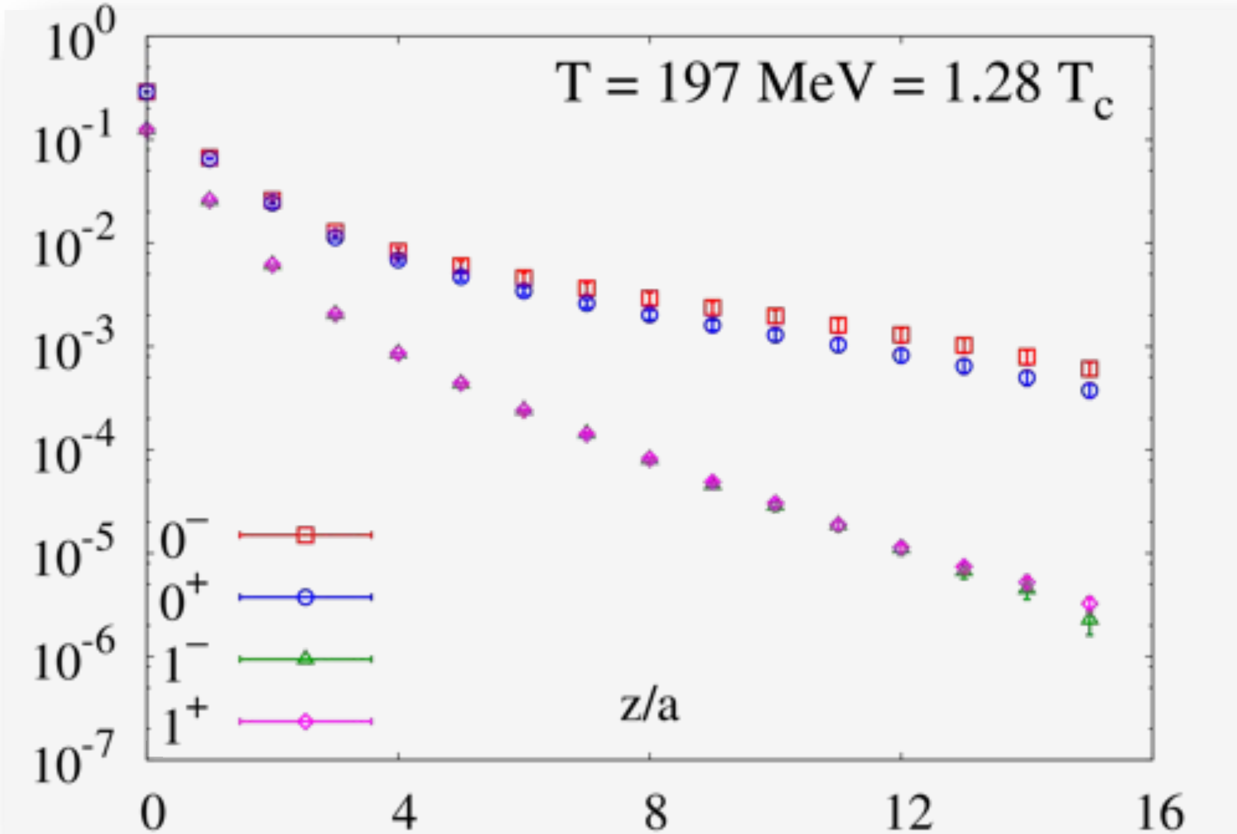

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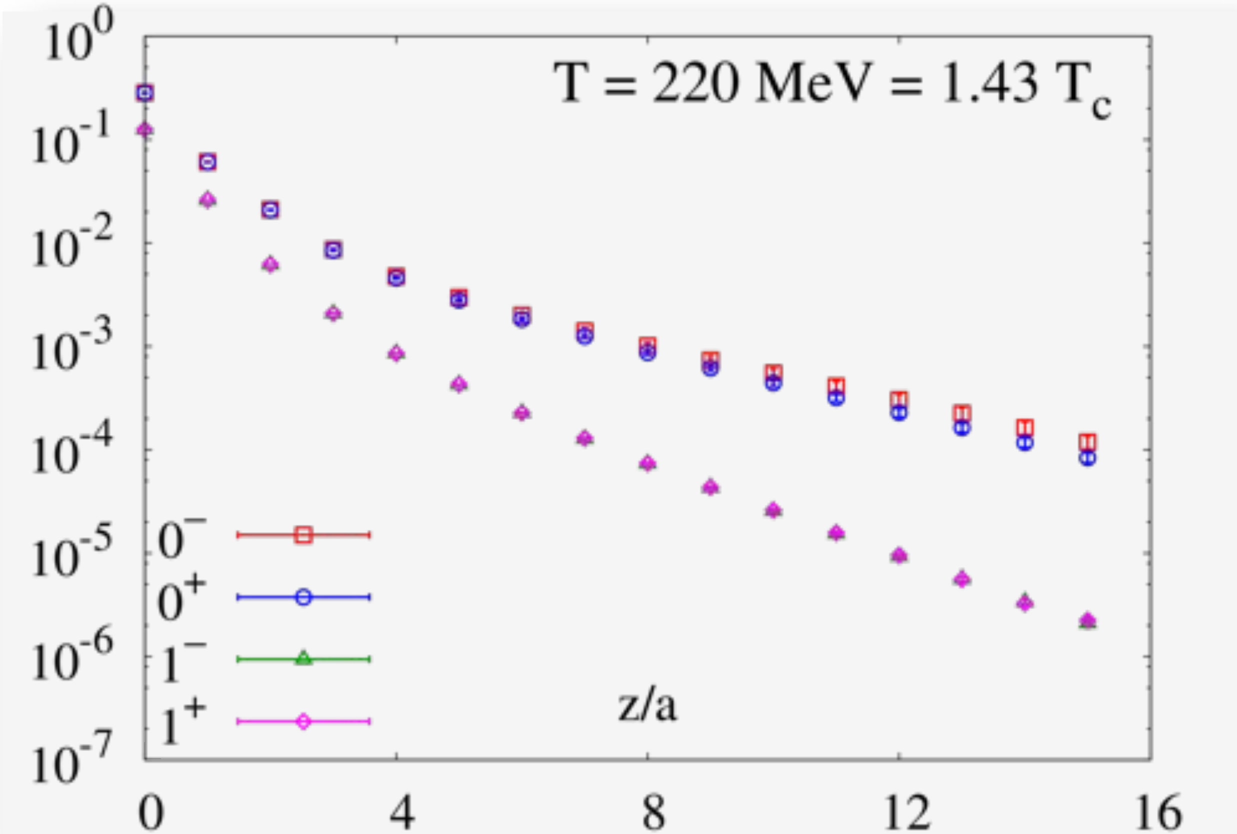

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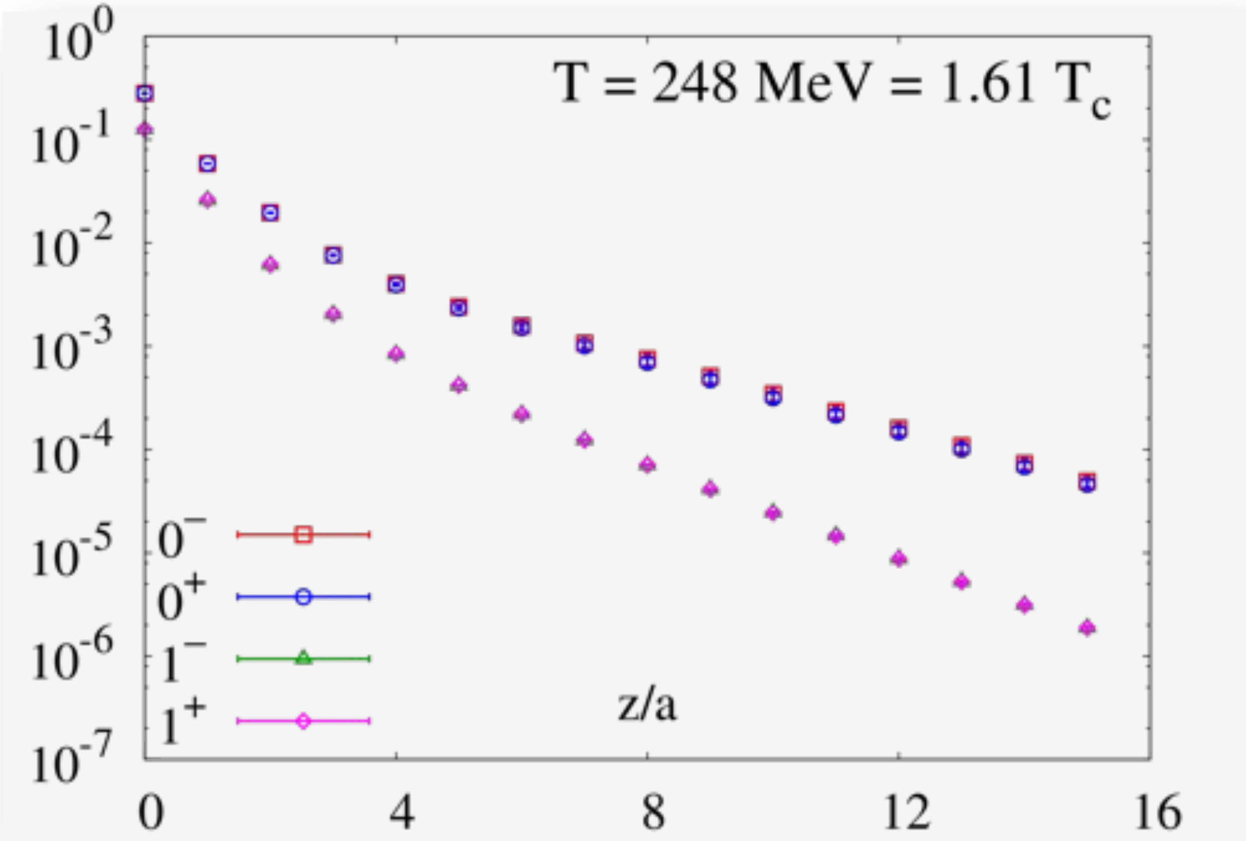

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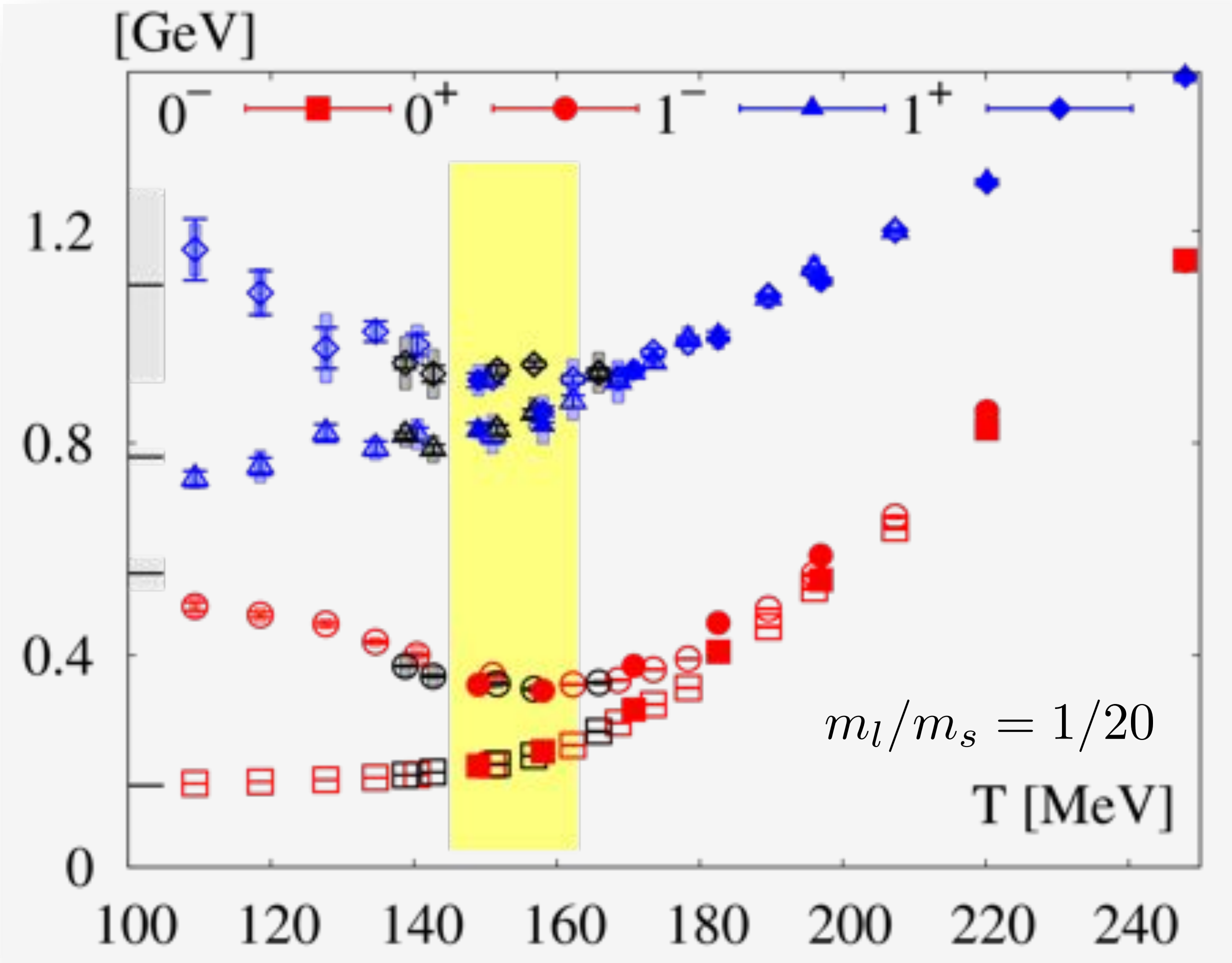
Restoration of broken symmetries

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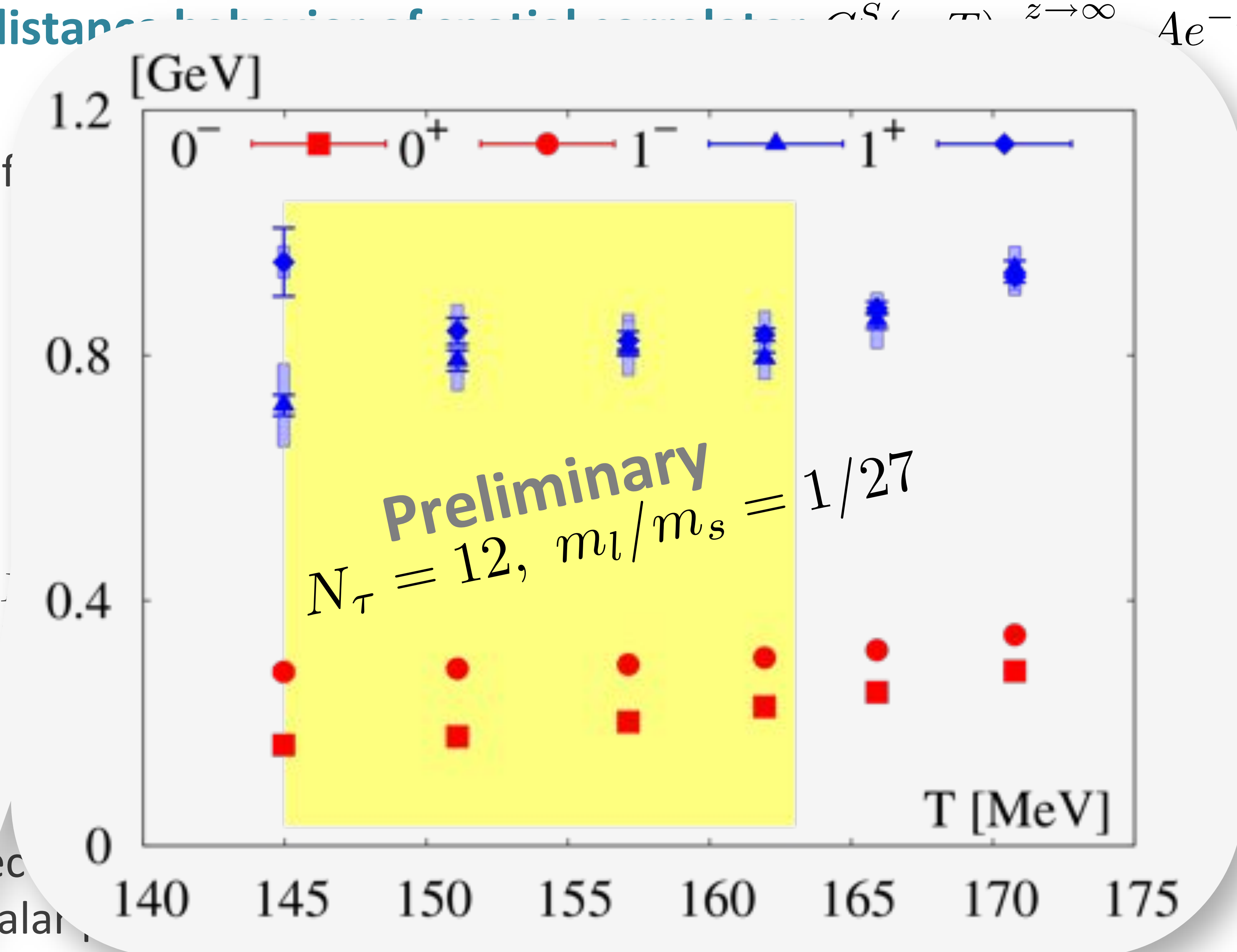
➡ chiral: restored, $U_A(1)$: broken at T_c, no dependence on lattice spacing

Restoration of broken symmetries

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

Light-unf...

Open: ...
Black: ...
Filled: ...



- Vec...
- Scalar ...

chiral: restored, $\mathrm{U_A}(1)$: 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: $G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

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in continuum and physical quark mass (preliminary)