Thermal modifications of meson states in lattice QCD and relations to heavy ion collisions

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- ✧ Full-QCD lattice simulations on physical point
- ✧ All mesons modified even below T_C except for charmonium
- ✧ Universal mass shifts depending on parity channels

PRD91 (2015) 5, 054503 & in preparation

Exotic hadrons from high energy collisions, YITP, Mar. 23--25

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Introduction

- Mesons in medium
- Lattice QCD simulations
  Full-QCD approach
  Spatial correlation functions

Lattice simulations

- Modification of spectral function
  appears all mesons below T_C,
  but charmonium stable beyond T_C
- Universal mass shift of screening masses

Summary & Discussions

Variety of mesons

up/down: $m_{ud} \sim$ 3--5 MeV, strange: $m_s \sim$ 95 MeV, charm: $m_c \sim$ 1.2 GeV...

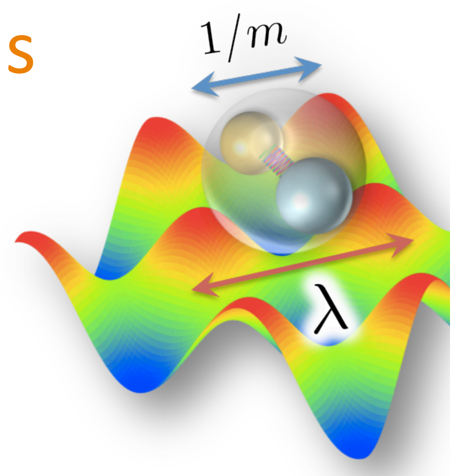
in vacuum

$[u\bar{d}]$ $[u\bar{s}]$ $[s\bar{s}]$ $[c\bar{u}]$ $[c\bar{s}]$ $[c\bar{c}]$

$\pi,\ \rho,\ K,\ K^*,\ \eta,\ \phi,\ D,\ D^*,\ D_s,\ D_s^*,\ \eta_c,\ J/\psi,\ \chi_c, \cdots$

0.1 0.5 1.0 2.0 3.0 mass [GeV]

In medium: modified due to thermal fluctuations



significant when: (thermal wavelength λ) $>$ (size $1/m$)

Modification pattern: Good probes of QCD matter

- Light mesons: sensitive to chiral properties

  scaling law Brown and Rho (1991)

  $$\sqrt[3]{\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle}} \approx \frac{f_\pi^*}{f_\pi} \approx \frac{m_\rho^*}{m_\rho}$$

  → mass shift? and restoration?

- Quarkonium: Sequential dissolution pattern

  J/ψ suppression Matsui and Satz (1986)

  → charmonium stable in quark-gluon plasma?

Lattice QCD simulations

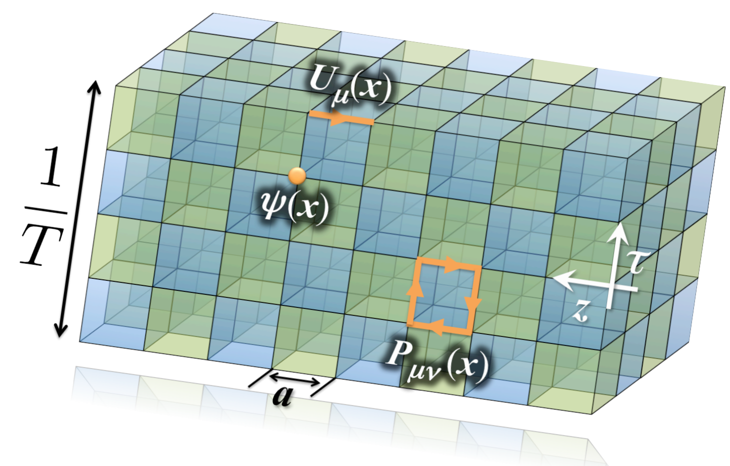
QCD: Strong non-linearity and infinite-dimensional integral

→ Field theory on lattice in Euclidean space

→ Monte-Carlo simulations based on importance sampling

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int D\bar{q} Dq DA\, \mathcal{O}(\bar{q}, q, A)\, e^{-S_{QCD}}$$

$$= \frac{1}{N_{\rm conf}} \sum_{\{U_i\}}^{N_{\rm conf}} \mathcal{O}(U_i) \pm O(\frac{1}{\sqrt{N_{\rm conf}}})$$



Fundamental parameters:

$\Lambda_{\rm QCD}, m_{u/d}, m_s, m_c$

determined at $T = 0$

→

Finite temperature:

Theoretical prediction in 1st principle calculations

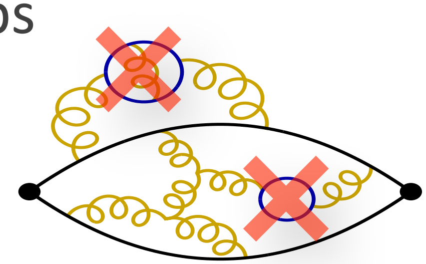
Applicable: Static & homogeneous system

(difficult: non-equilibrium, time dependent, high density…)

Key: **Full(2+1)-QCD simulations on physical point**

⇔ e.g.) Quenched simulations: neglect quark-loops

$$Z_{\rm QCD} = \int dU \det D(U) e^{-S_{\rm gluon}}$$



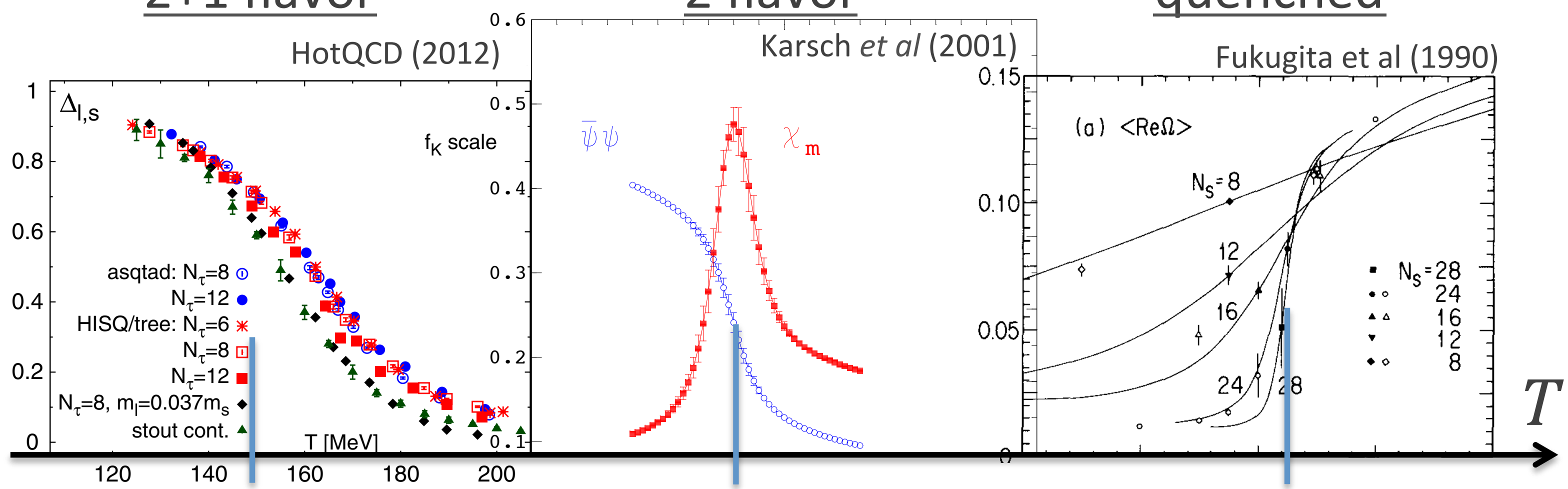
$\mathrm{T}=0$: Reproduce physical hadron spectra within 10-20% deviations

CP-PACS Coll. (2000)

$\mathrm{T}>0$: Significant discrepancy, e.g. phase transition

Quenched: 1st order PT ➡ Full(2+1 and 2): Crossover PT

2+1 flavor | 2 flavor | quenched



$\mathrm{T_C} = 154 \pm 9$ MeV | 173 ± 8 MeV | 270 MeV

Full-QCD simulations: indispensable for thermal properties

Mesons on lattice

difficult at finite temperature...

Temporal correlation function

e.g.) $J_H = \bar{q}\Gamma_H q$

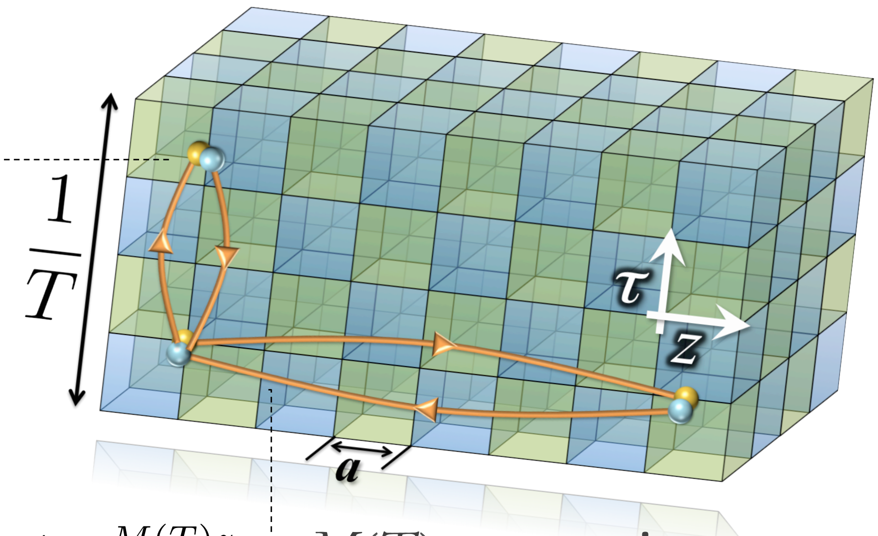
$$G(\tau) = \int d^3x \langle J_H^\dagger(\tau, \mathbf{x}) J_H(0, \mathbf{0})\rangle = A_0 e^{-m_0\tau} + A_1 e^{-m_1\tau} + \cdots$$

1^{st} excited state ($m_1 > m_0$)

Ground state: dominant at large τ

Physical limitation $\tau < 1/T$:

difficult to access thermal modification



Spatial correlation function

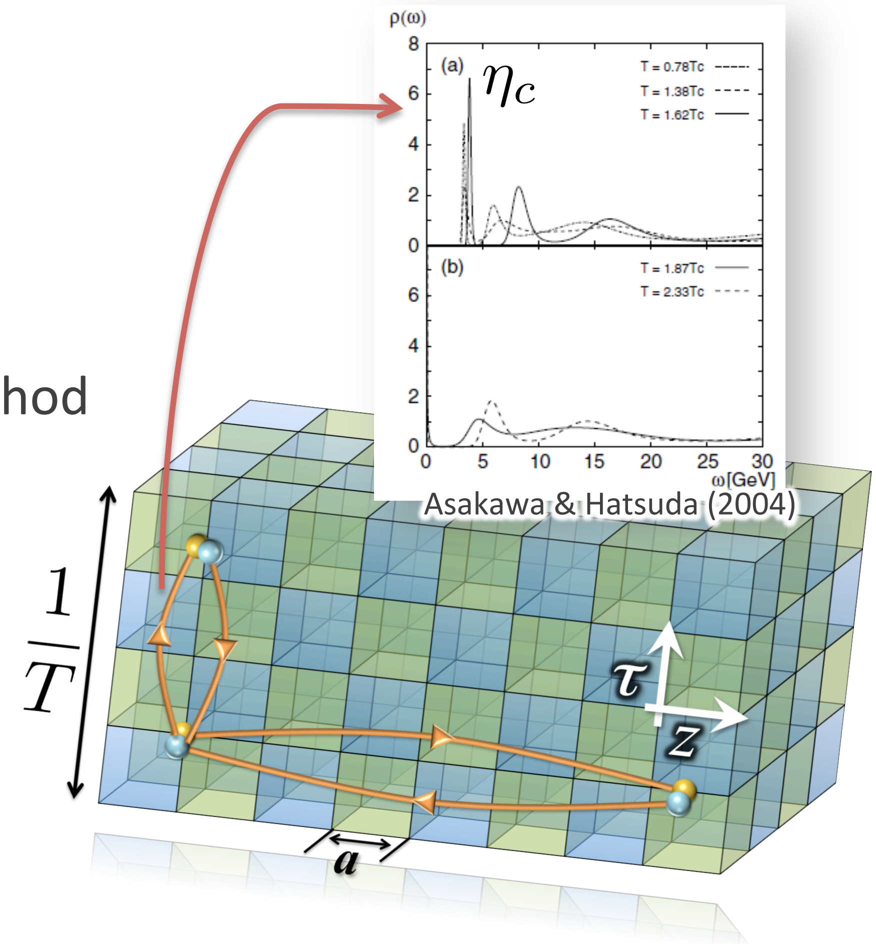
$$G^S(z,T) = \int_0^{1/T} d\tau \int dxdy \langle J_H(\tau, \vec{x}) J_H(0, \vec{0})\rangle \xrightarrow{z\to\infty} Ae^{-M(T)z}$$

$M(T)$: screening mass

No limitation: more sensitive to in-medium modification

Mesons on lattice

Spectral function $\sigma(\omega, T)$ ∈ pole mass, width and thermal modification...



Asakawa & Hatsuda (2004)

Temporal correlation function

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

Reconstruction of σ : Maximum Entropy Method
large # of time separation: necessary
almost done in Quenched approx.

Spatial correlation function

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

No T dependence in Kernel

$G^S(z, T)/G^S(z, T = 0)$: direct probe of thermal modification of σ
accessible in Full-QCD simulations

Mesons on lattice

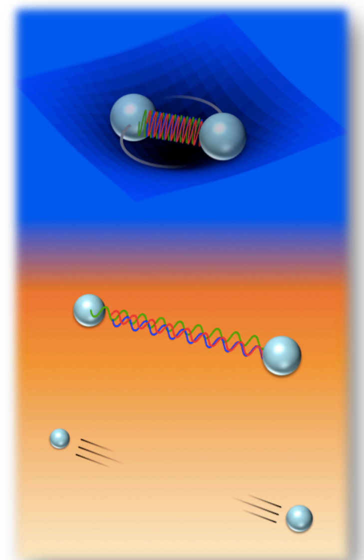
<u>Spatial correlation function</u>

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

$M(T)$: screening mass

Behavior in limiting cases:

At low T, bound state w/o thermal effect:



$\Rightarrow$ $G^S(z,T)/G^S(z,T=0) = 1$
$M(T) \sim m_0$ pole mass at $T=0$

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

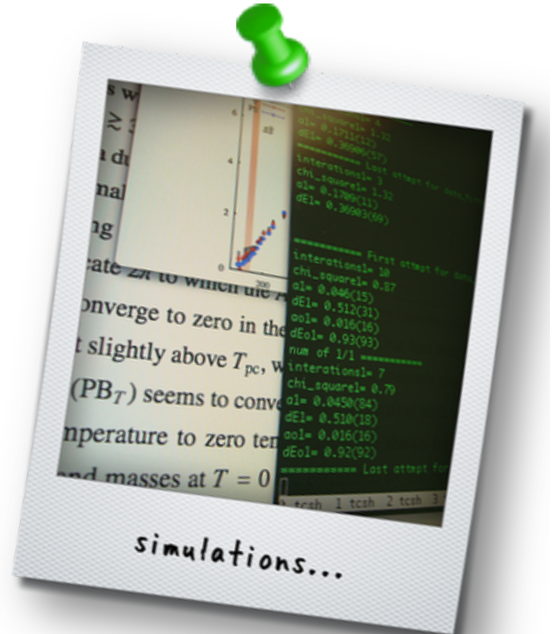
At $T \sim T_c$, in-medium modification and/or dissolution:

$\Rightarrow$ $G^S(z,T)/G^S(z,T=0) \neq 1$
$M(T)$: Leading response of mass shift
$M(T) > m_0$ or $< m_0$?

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

with the lowest Matsubara frequency

Lattice QCD simulations



- 2+1 flavor QCD in HISQ action HotQCD `11, `14 (charm quenched)
- m_s: physical, $m_l/m_s = 1/20$ (m_π~160 MeV, m_K~504 MeV)
- N_τ= 8, 10, 12: keeping N_s/N_τ=4 ➡ continuum limit
- 32^4--48^3x64 at $T = 0$
- scale: f_k input
- calculating quark-line connected part

Mesons

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^+	a_1	K_1	D_1	$f_1(1420)$	D_{s1}	χ_{c1}

Thermal modifications

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

Screening masses

$$G^S(z,T) \to Ae^{-M(T)z}$$

Ratio of spatial correlation functions

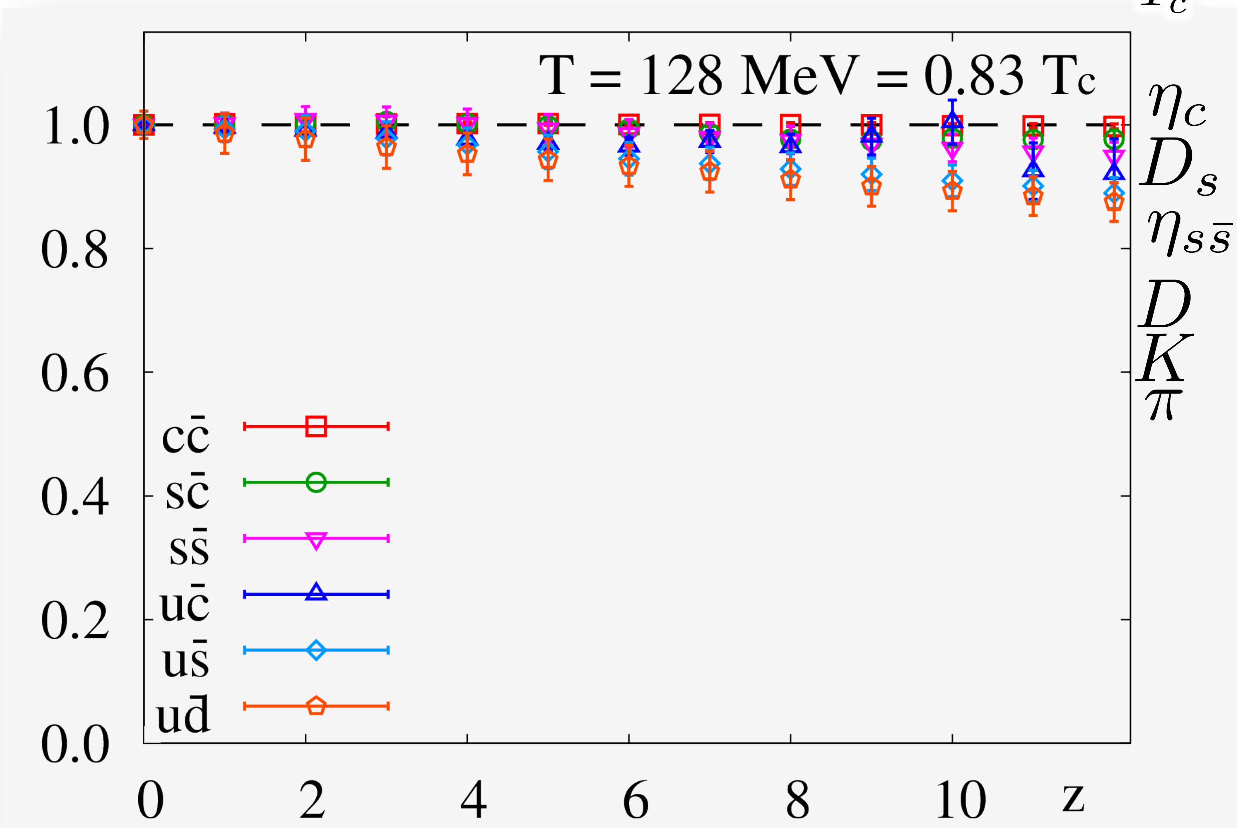
Probe of thermal modifications of spectral function

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

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar

$J^P = 0^-$



- modification even at $T < T_c$, except for charmonium
- significant flavor dependence at $T > T_c$,

  but no change on η_c: modified at $T \gtrsim 1.3\, T_c$

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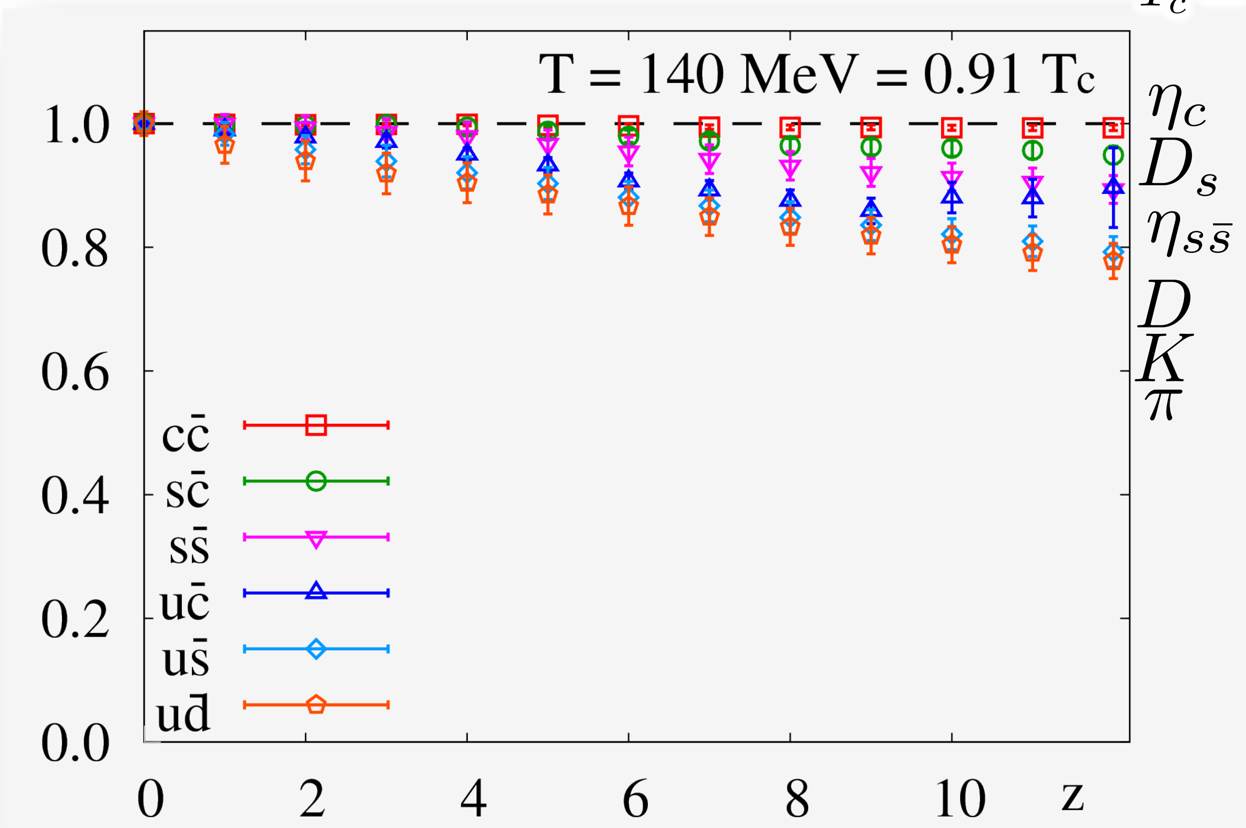

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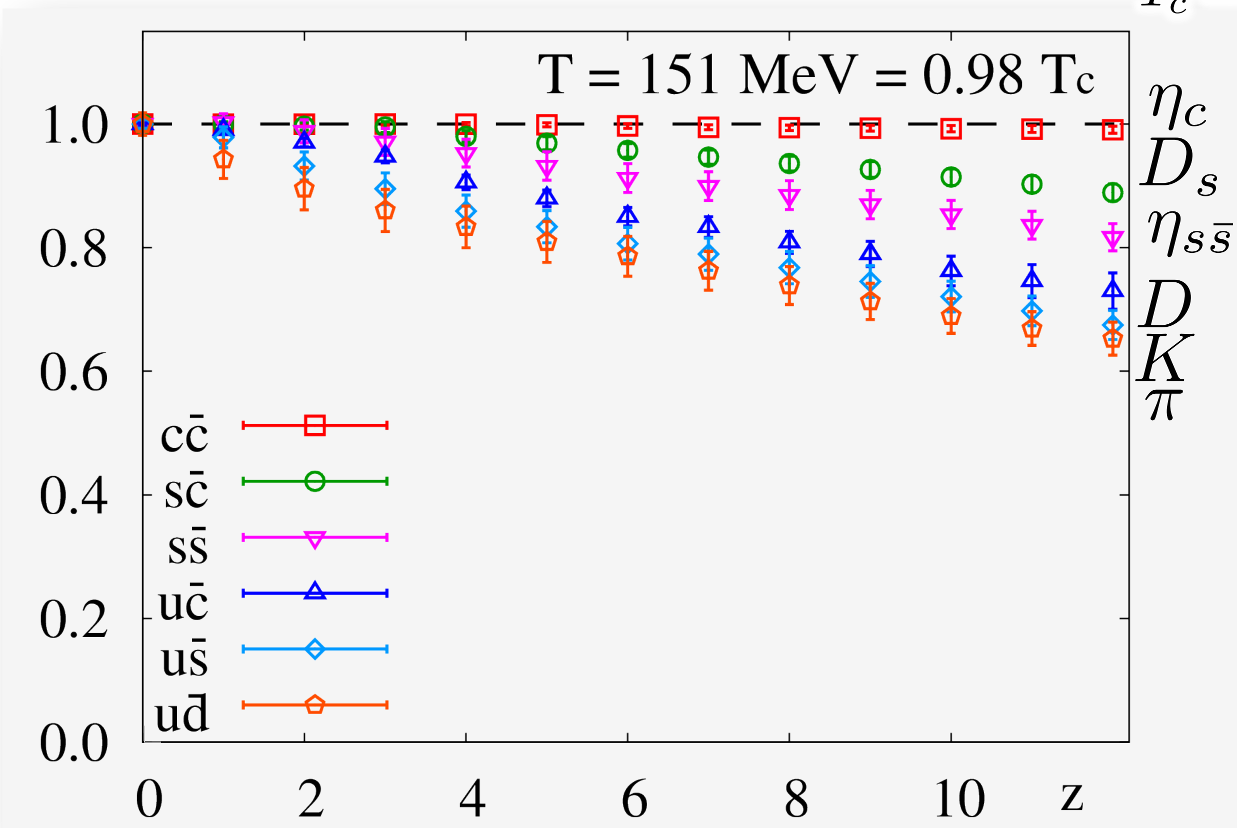

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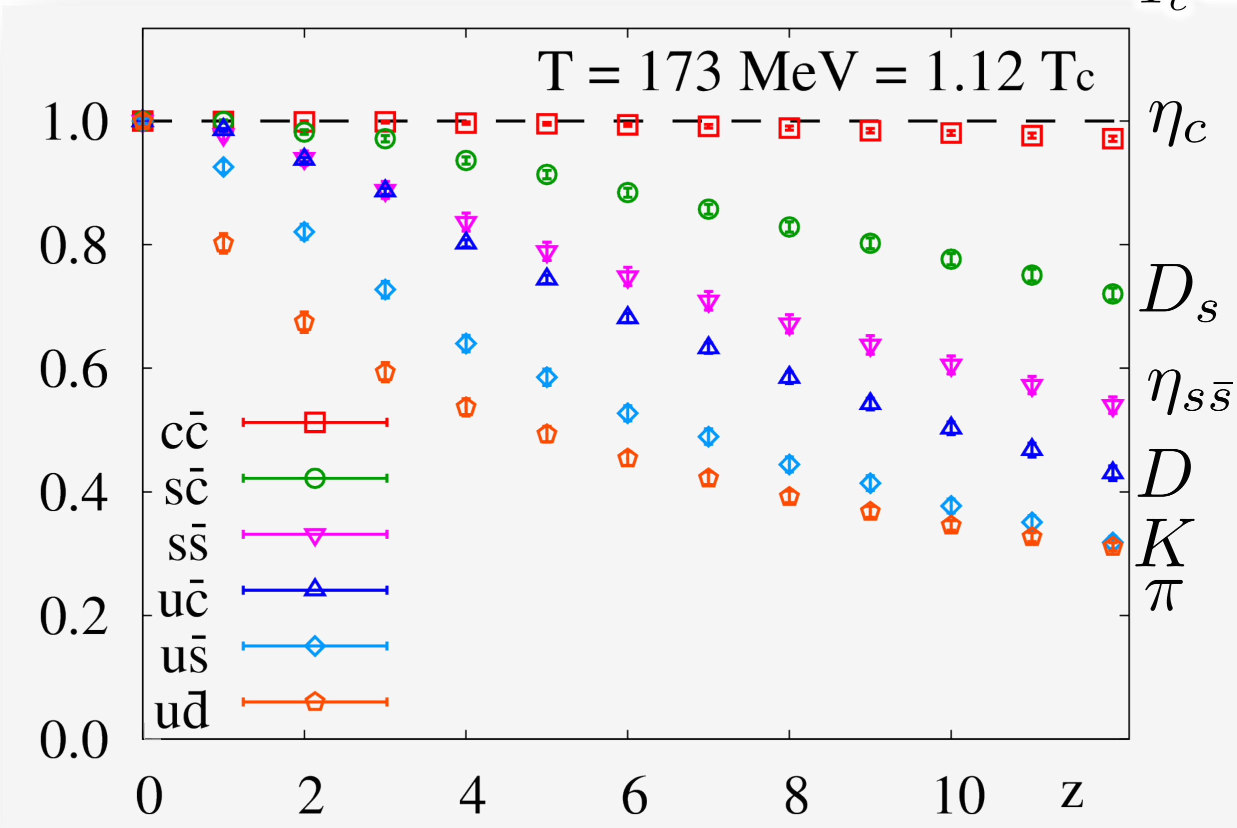


- modification even at $T < T_c$, except for charmonium
- significant flavor dependence at $T > T_c$,

but no change on η_c: modified at $T \gtrsim 1.2$--$1.3\,T_c$

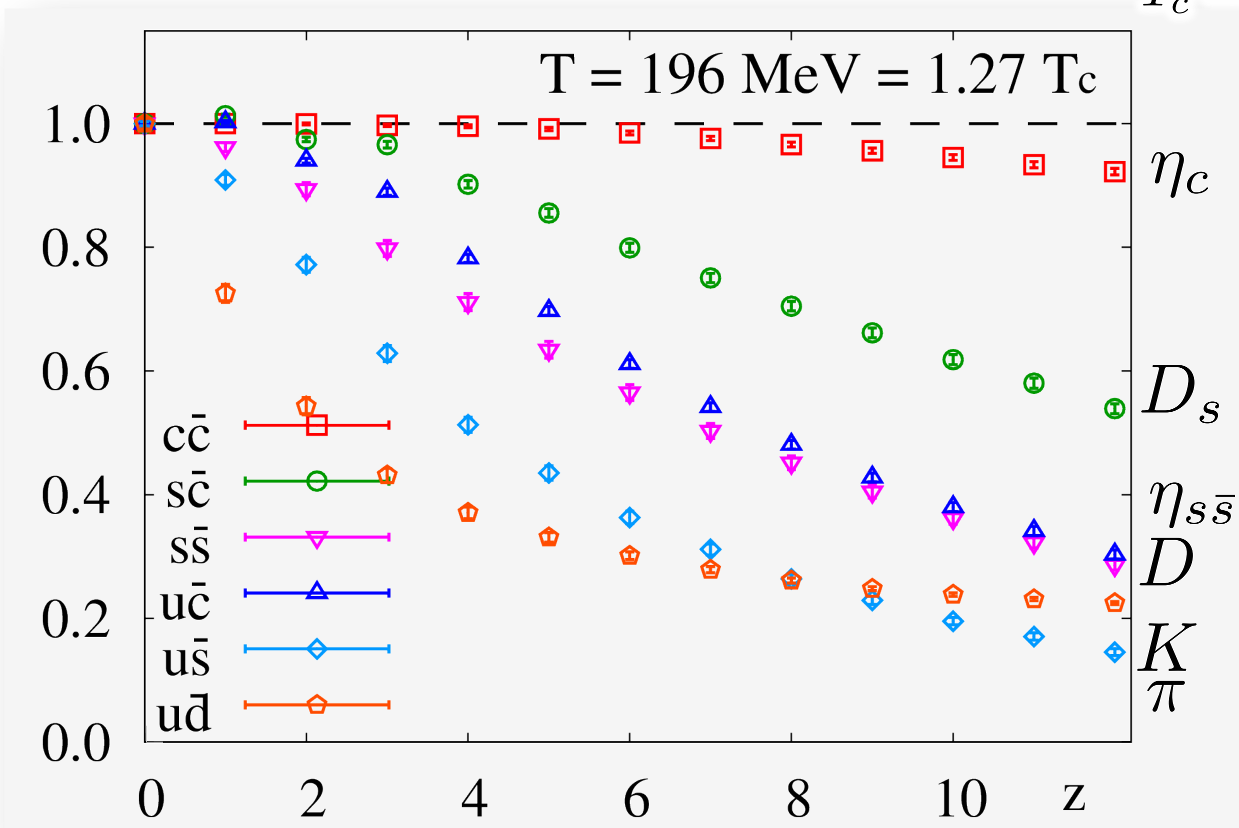
Ratio of spatial correlation functions

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 $J^P = 0^-$

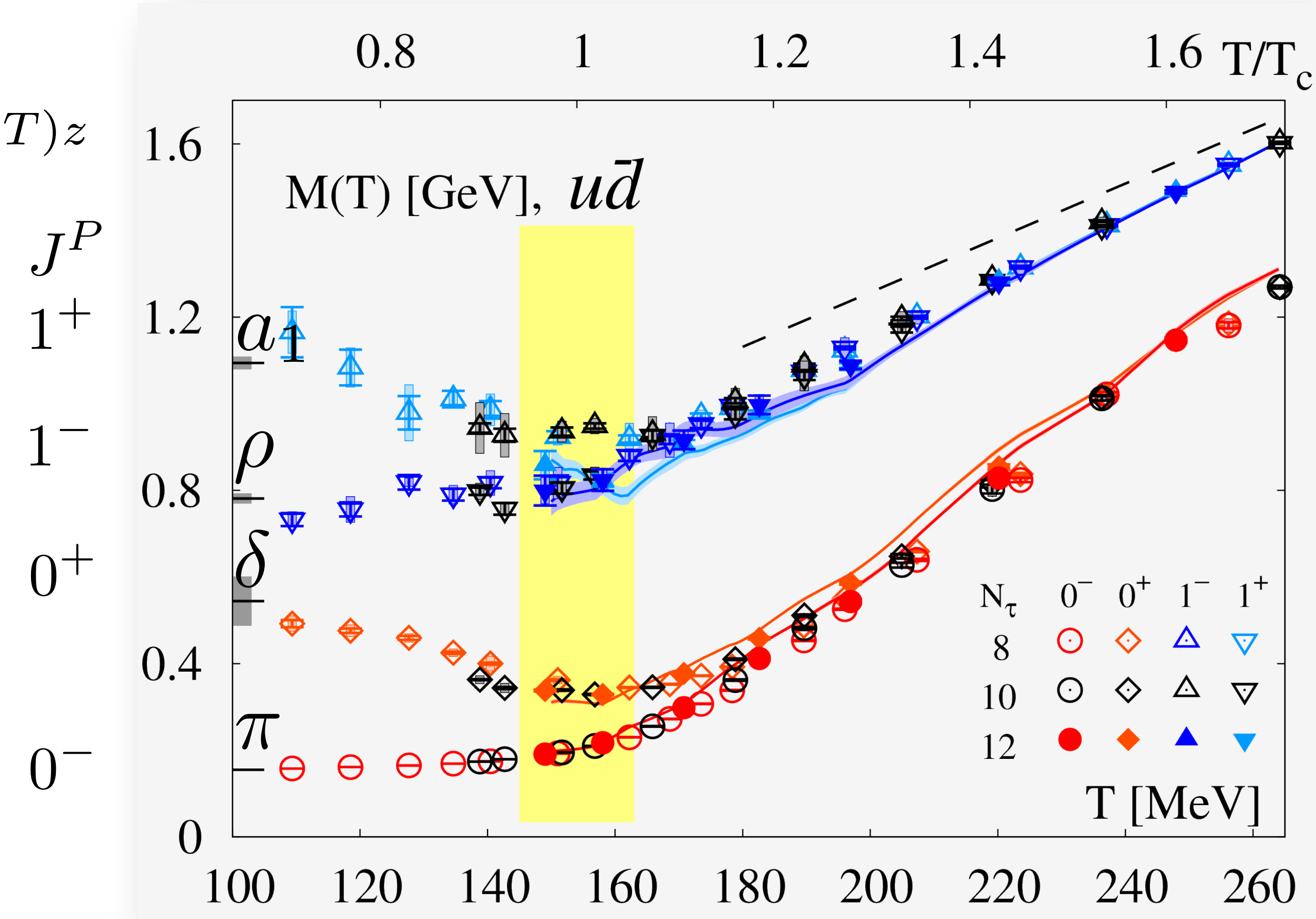


- modification even at $T < T_c$, except for charmonium
- significant flavor dependence at $T > T_c$,

  but no change on η_c: modified at $T \gtrsim 1.2$--$1.3\, T_c$

Screening mass in light mesons

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



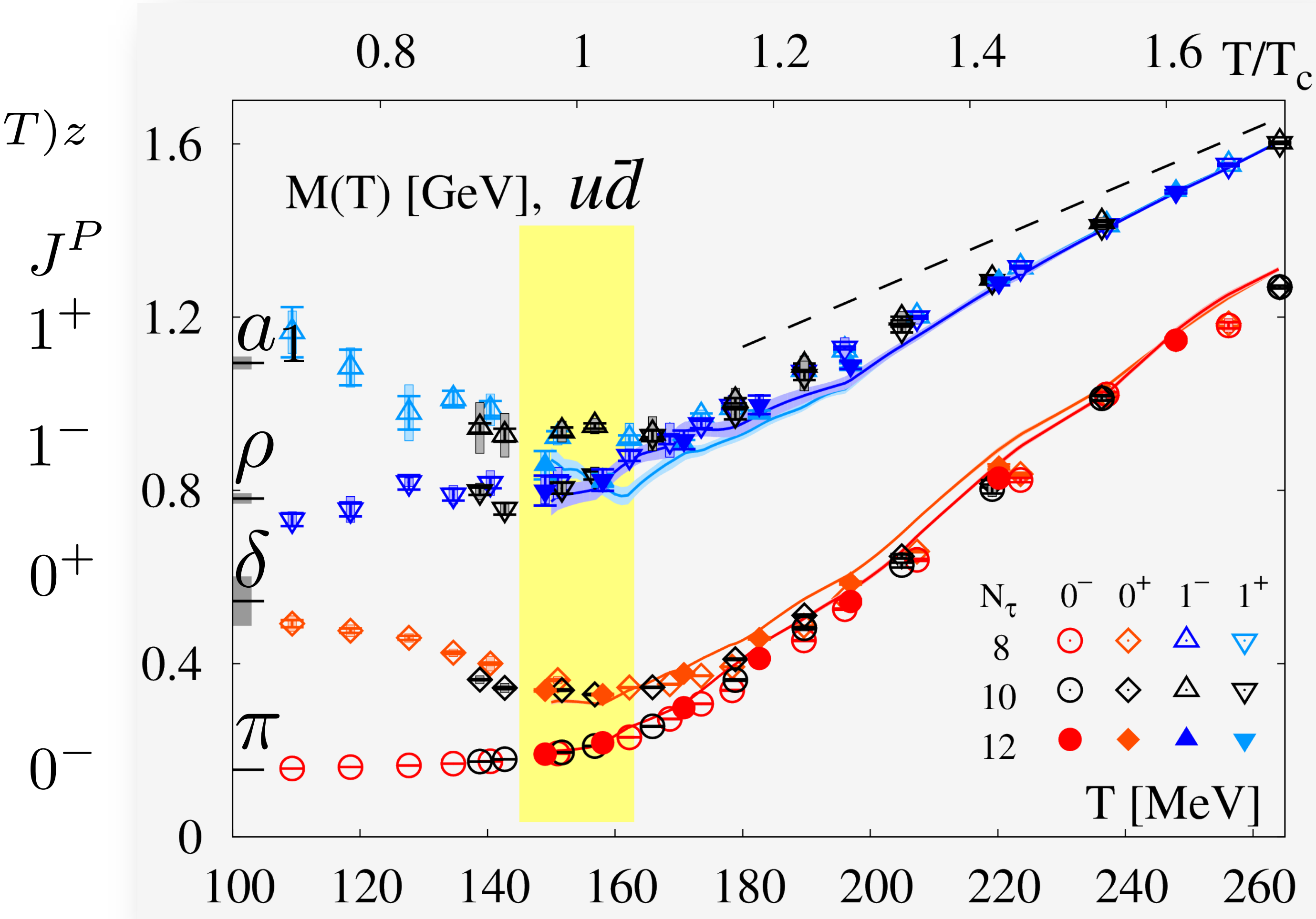
mass shift

- P− : not significant at $T < T_c$, monotonically increasing at $T > T_c$
- P+ : decreasing at $T < T_c$, increasing at $T > T_c$
- Almost linear at $T > 1.2T_c$ → no mesonic bound states

cf.) dashed line: free limit $M \to 2\sqrt{m_q^2 + (\pi T)^2}$

Screening mass in light mesons

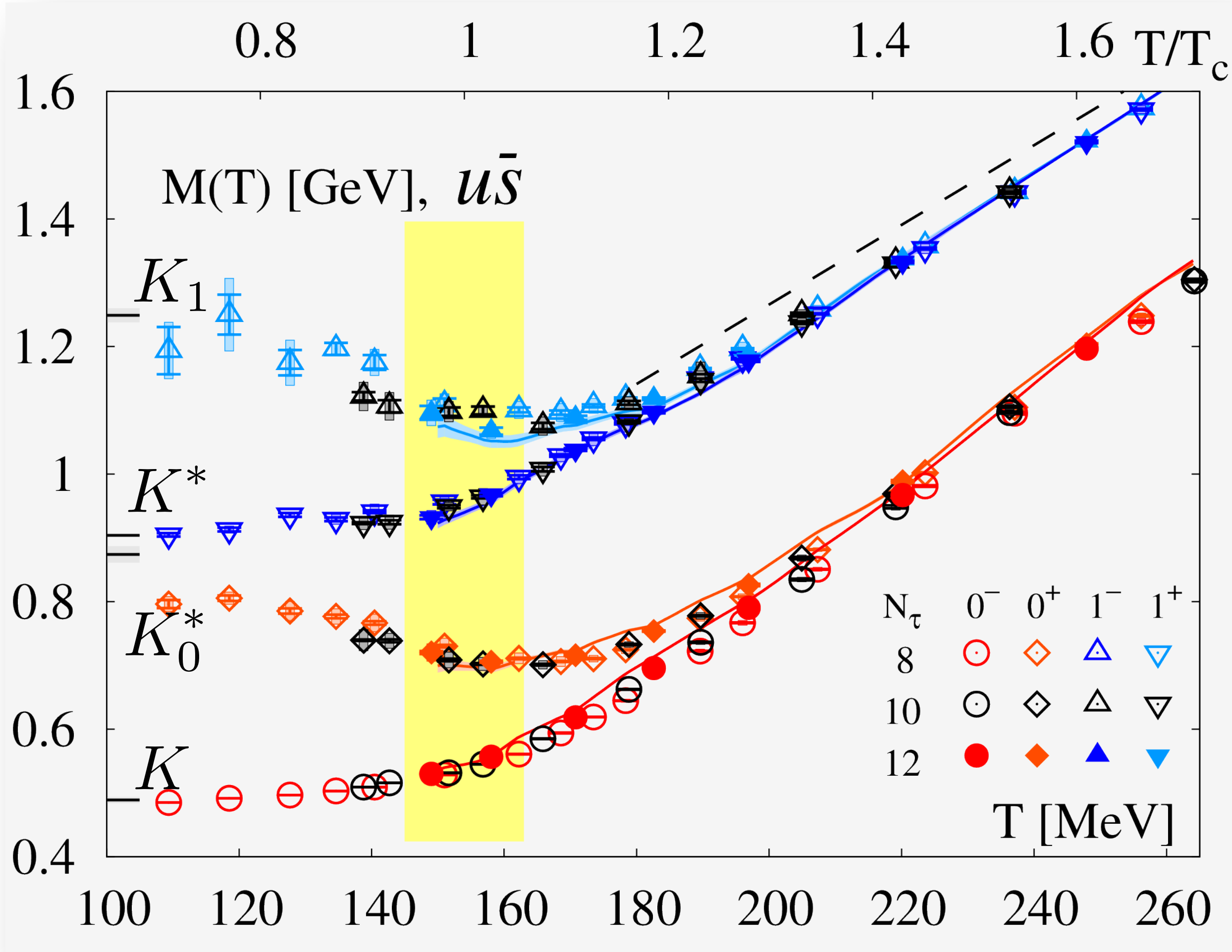
$$G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$$



<u>Restoration of broken symmetries</u>

- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$ ➡ chiral
- Scalar partner degenerates at $T \sim 1.4T_c$--$1.6T_c$ ➡ chiral + $U_A(1)$

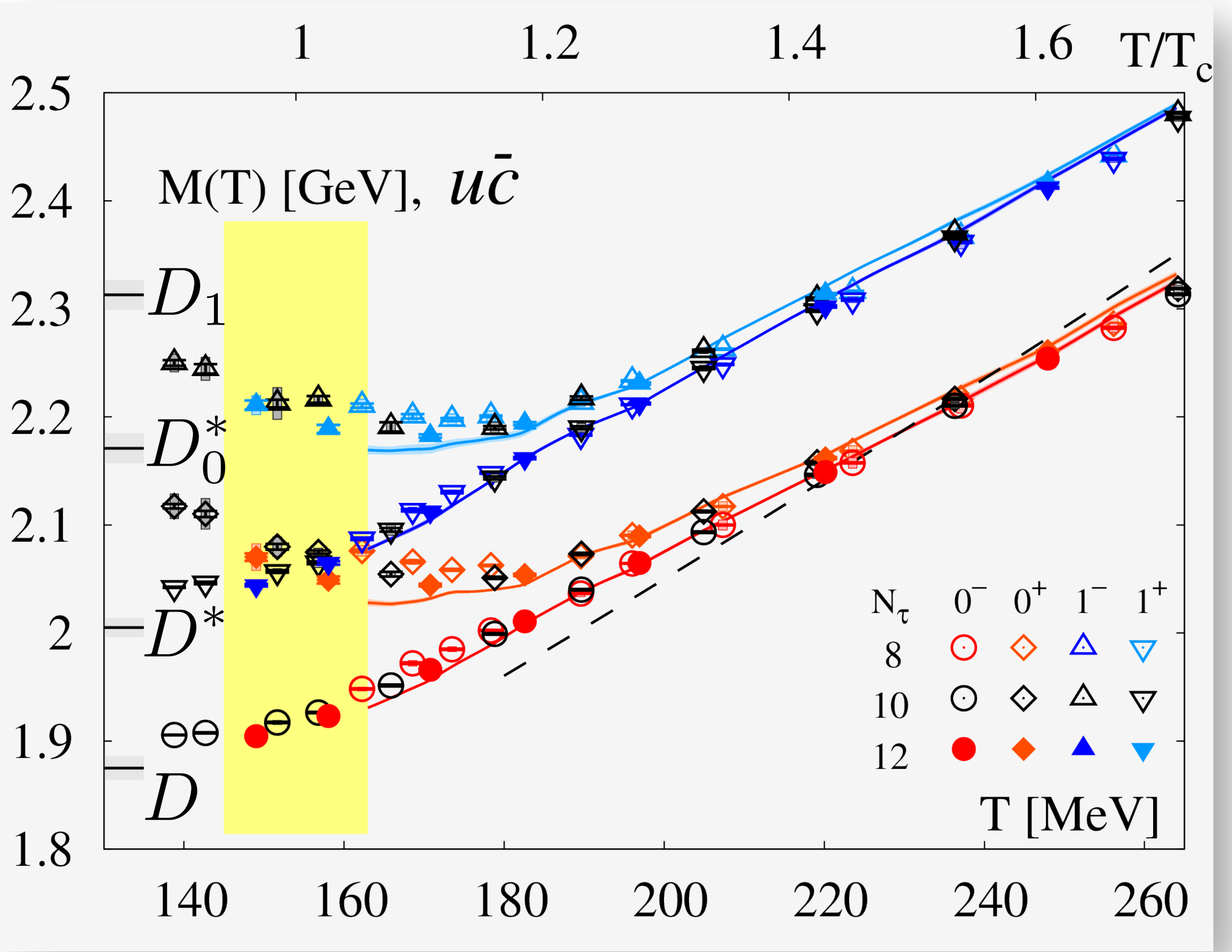
Flavor dependence



Restoration pattern

- Similar to $u\bar{d}$
- Degeneracies appear at $T \sim 1.3 T_C$ for vector and $T \sim 1.6 T_C$ for scalar

Flavor dependence

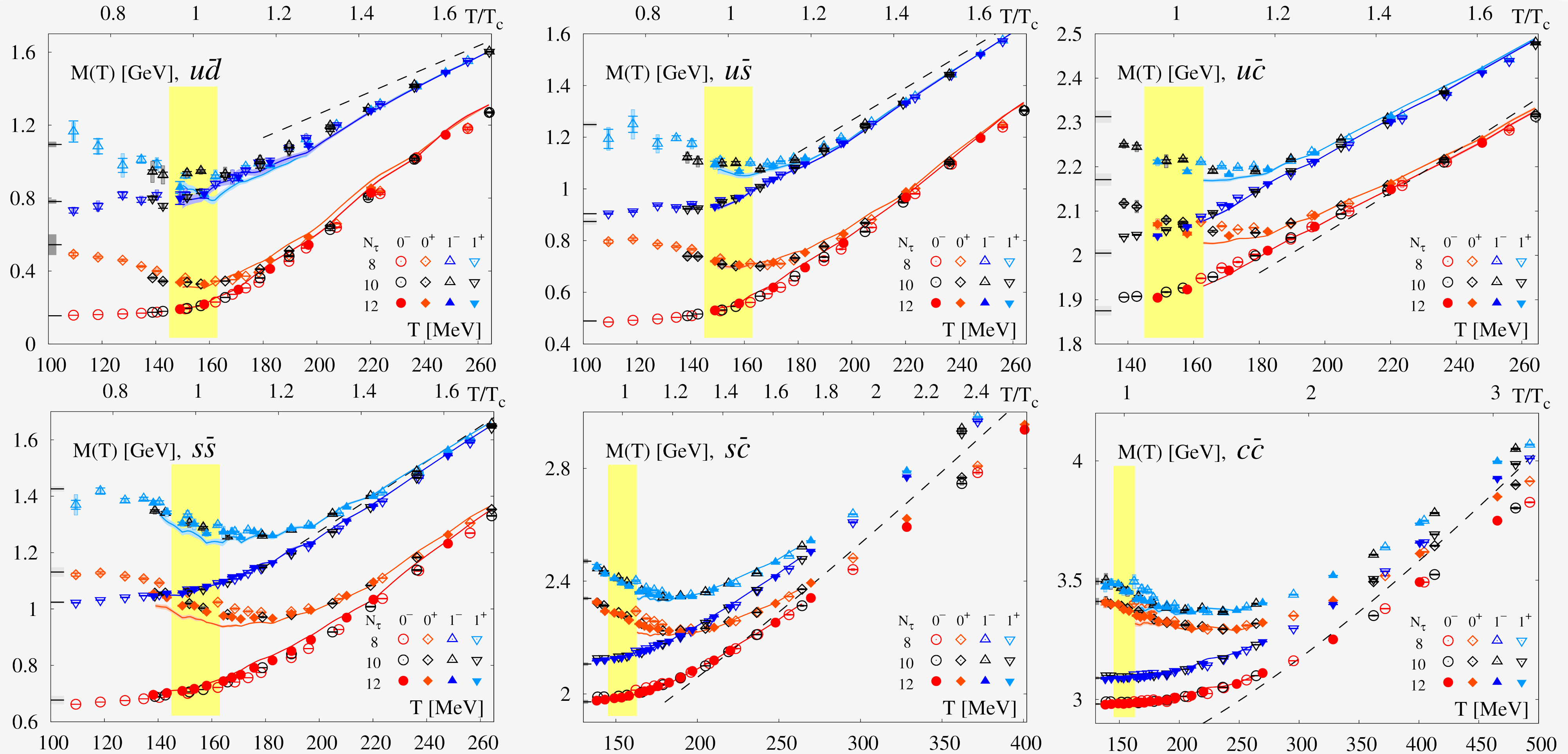


Restoration pattern

- Similar to $u\bar{d}$
- Degeneracies appear at $T\sim1.6T_C$ for both vector and scalar

➡ restoration of chiral: depend on flavors
$U_A(1)$: independent

Flavor dependence



Universal mass shift: P− increasing monotonically

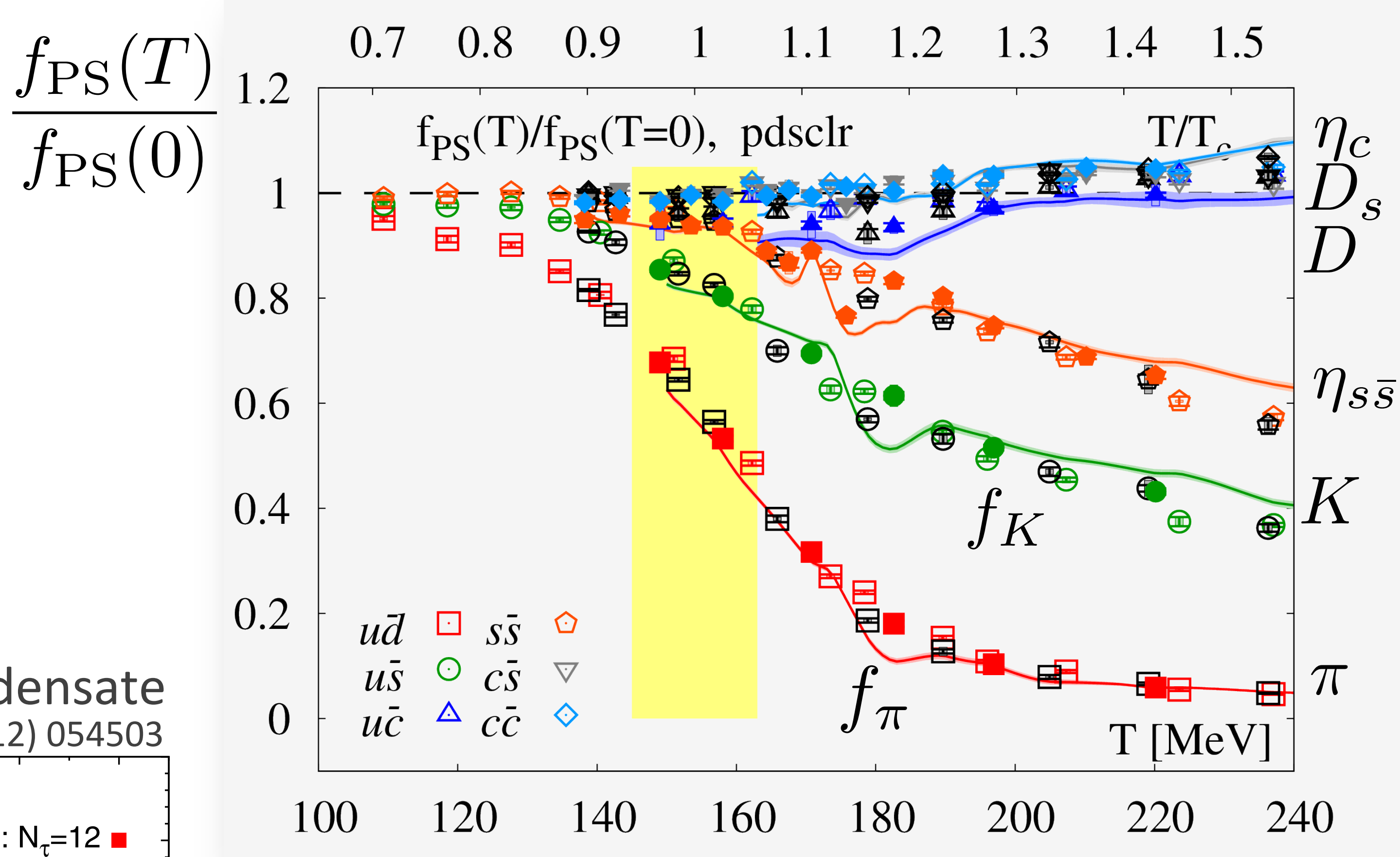
P+ decreasing first and increasing above some T

Scale (chiral restored T): depend on flavors

trivial? or…? effective scale: further different from chiral to heavy quarks

$m_{ud} \simeq 3\text{–}5\ \text{MeV},\ m_s \simeq 95\ \text{MeV},\ m_c \simeq 1.2\ \text{GeV}$

Leptonic decay constant



Renormalized chiral condensate

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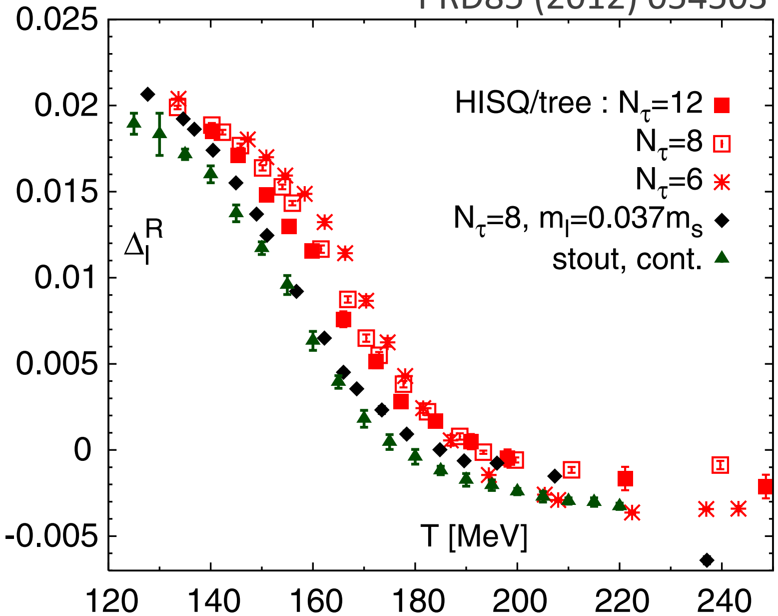

decreasing with T increasing for $u\bar{d}, u\bar{s}$ and $s\bar{s}$

no significant T dependence for $u\bar{c}, s\bar{c}$ and $c\bar{c}$

Lattice indicates: $\sqrt[3]{\frac{\langle \bar{q}q\rangle^*}{\langle \bar{q}q\rangle}} \approx \frac{f_\pi^*}{f_\pi}$ ✗ $\frac{m_\rho^*}{m_\rho}$

Summary

Full-QCD lattice simulations on physical point

In-medium mesons from spatial correlation functions:

- sensitive to thermal modifications
- probe of modification of spectral function $G^S(z,T)/G^S(z,T=0)$

All meson modified even below T_c except for charmonium

In heavy-ion collision,

- Signal of creating quark-gluon plasma
  - ➡ modification of charmonium (η_c and J/ψ)
- Thermal effect: appears on other meson states
- Restorations of broken symmetries: parity partners

Universal mass shift depending on parity channels

T dependence of screening mass: $G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

- Leading response of mass shift
- $\mathrm{P-}$ increasing monotonically
- $\mathrm{P+}$ decreasing first and then increasing
- Different from chiral effective approach

$$\sqrt[3]{\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle}} \approx \frac{f_\pi^*}{f_\pi} \approx \frac{m_\rho^*}{m_\rho}$$