Study on charmonium and bottomonium correlation functions in lattice QCD at finite temperature

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Quarkonium in hot medium

At extremely high temperature and density

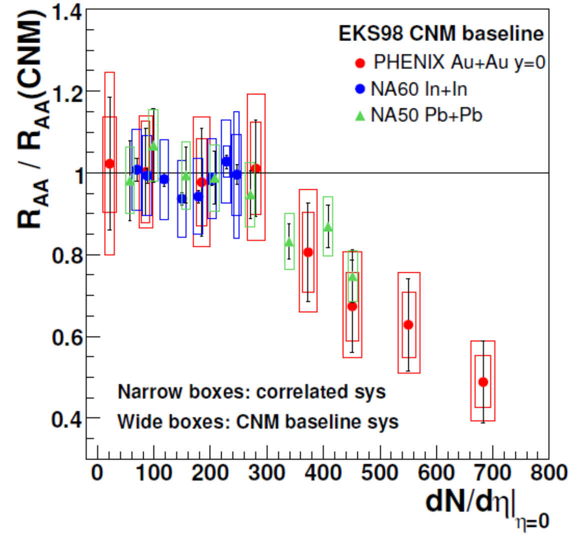
⬇ Deconfinement of quarks and gluons

Quark Gluon Plasma (QGP)

The Debye screening prevents heavy quark-antiquark bound state (quarkonium) formation above a certain dissociation temperature

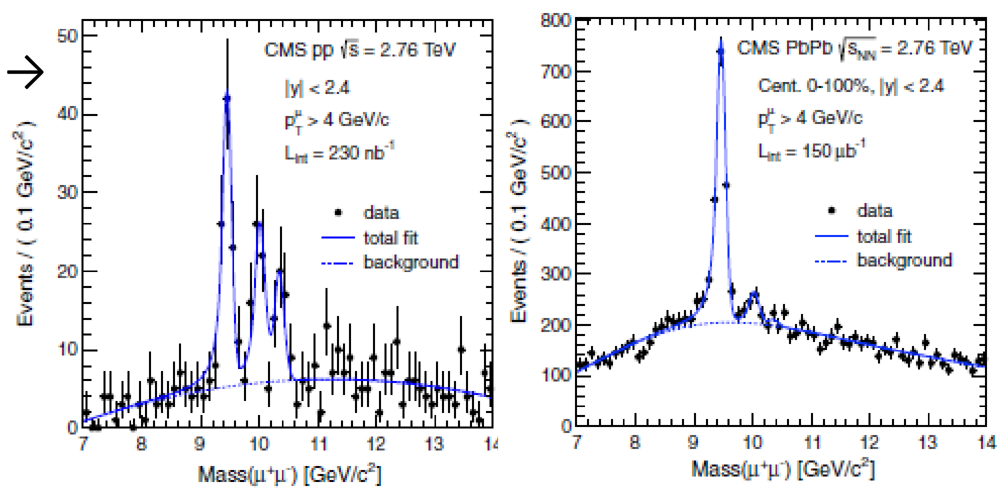
→ important probe of QGP created in heavy ion collisions
@ RHIC, LHC

T. Matsui and H. Satz, PLB 178 (1986) 416



N. Brambilla *et al.*, EPJ C71 (2011) 1534

Sequential Bottomonium suppression @ LHC →



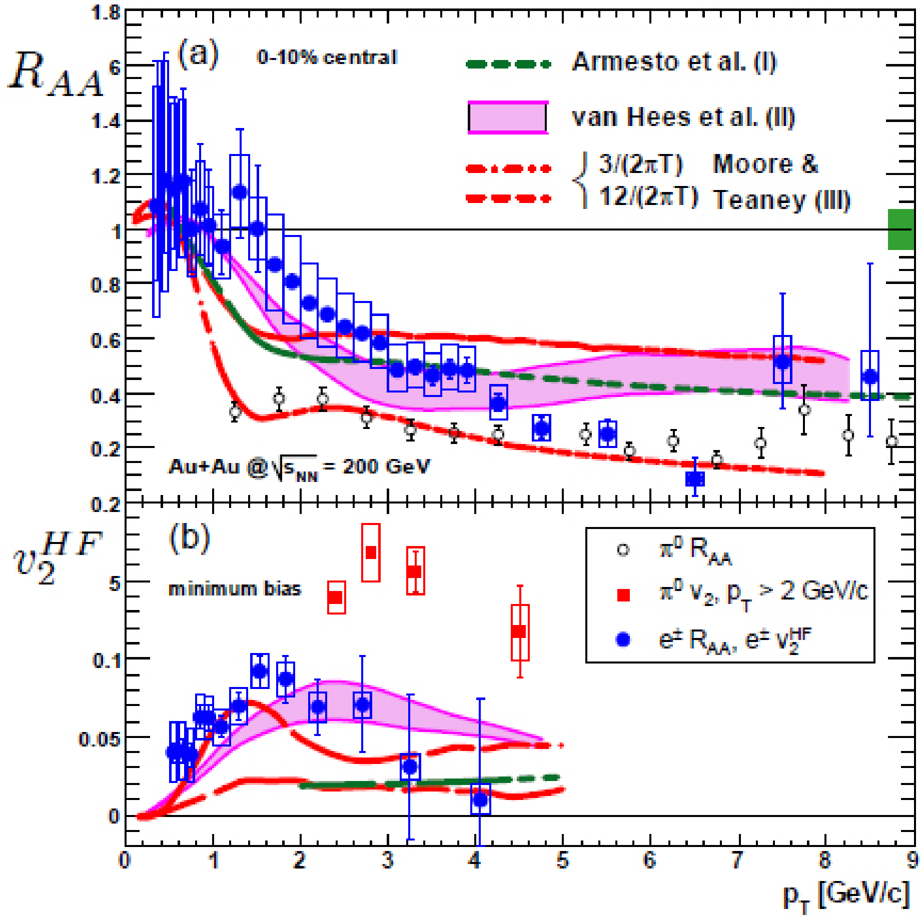
Investigating dissociation temperatures of charmonia and bottomonia by first principle lattice QCD calculation is important

S. Chatrchyan *et al.*, PRL 109 (2012) 222301

Transport coefficient

The evolution of the system in hydro models

← **Transport coefficients are important.**



Determination by the first principle calculation in QCD is needed.

Adare *et al*. [PHENIX Collaboration], PRL 98 (2007) 172301

Meson correlator & spectral function

Temporal Euclidian meson correlator

$$G_H(\tau,\vec{p}) \equiv \int d^3x e^{-i\vec{p}\cdot\vec{x}} \langle J_H(\tau,\vec{x}) J_H(0,\vec{0}) \rangle$$

$$= \int_0^\infty \frac{d\omega}{2\pi} \boxed{\rho_H(\omega,\vec{p})} K(\omega,\tau)$$

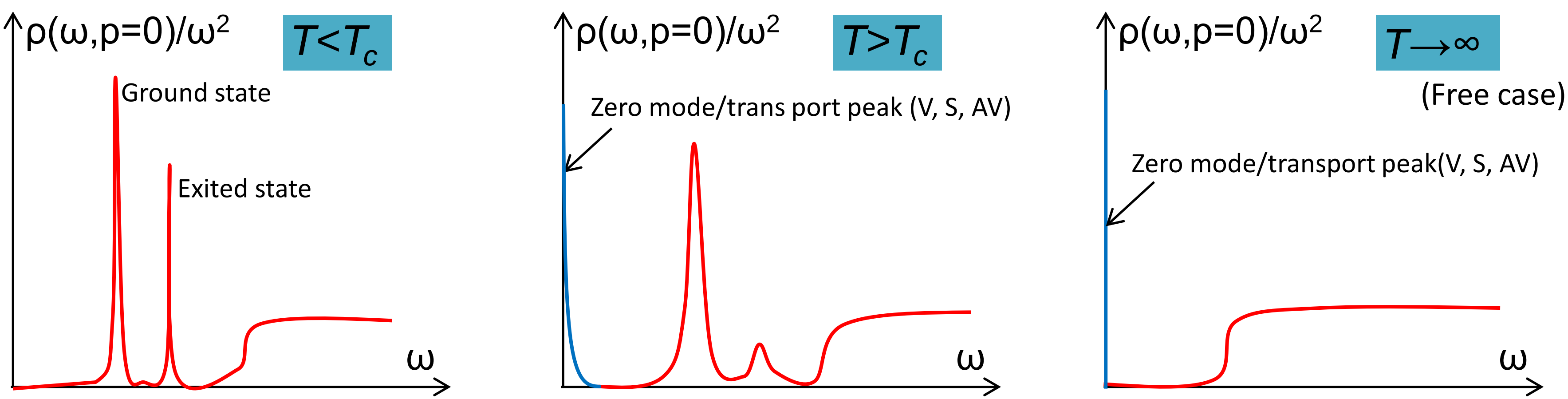
Spectral function

has all information about in-medium meson properties

$$J_H(\tau,\vec{x}) \equiv \bar{\psi}(\tau,\vec{x}) \Gamma_H \psi(\tau,\vec{x})$$

$$K(\omega,\tau) \equiv \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

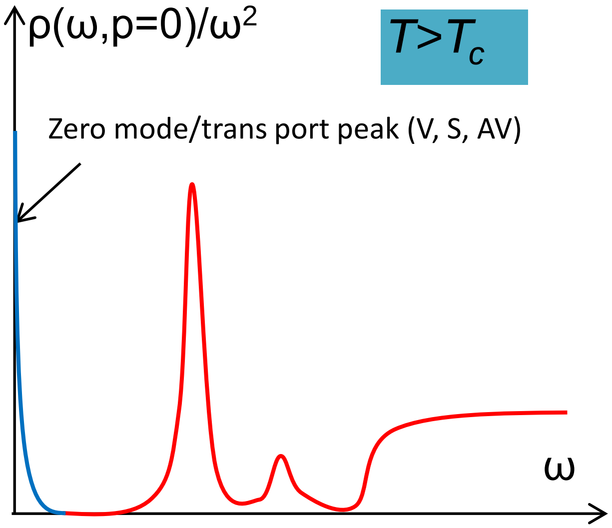
Channel	Γ_H	$^{2S+1}L_J$	J^{PC}	Quarkonia
Pseudoscalar (PS)	γ_5	$^1S_0$	0^{-+}	η_c, η_b
Vector (V)	γ_i	$^3S_1$	1^{--}	J/ψ, Υ
Scalar (S)	$\mathbf{1}$	$^1P_0$	0^{++}	χ_{c0}, χ_{b0}
Axialvector (AV)	$\gamma_i\gamma_5$	$^3P_1$	1^{++}	χ_{c1}, χ_{b1}



Heavy quark diffusion constant

$$D = \frac{1}{6\chi_{00}} \lim_{\omega \to 0} \sum_{i=1}^{3} \frac{\rho_{ii}^{V}(\omega, \mathbf{0})}{\omega}$$

$\rho_{ii}^{V}(\omega)$: spatial component of vector spectral function



χ_{00} : Quark number susceptibility

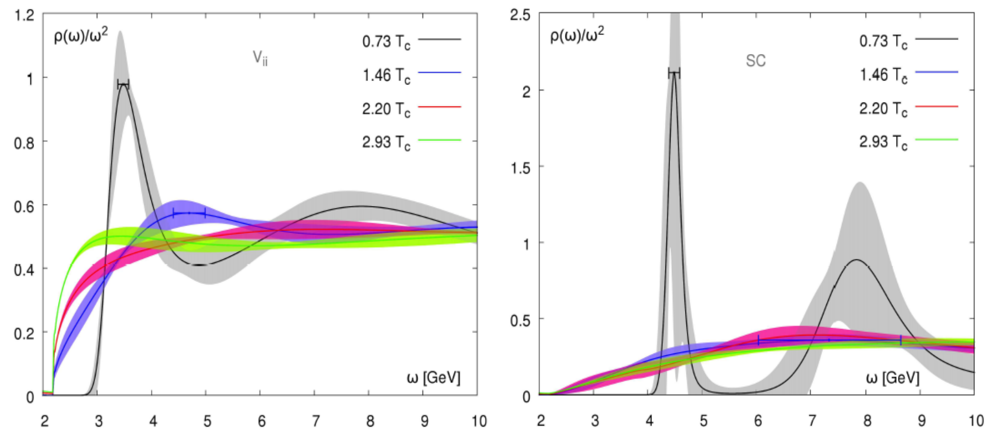
$\rho_{00}^{V}(\omega) = 2\pi\chi_{00}\omega\delta(\omega)$ ➡ $G_{00}^{V}(\tau) = T\chi_{00}$

D is related to the vector spectral function around zero frequency.

Recent lattice studies : spectral functions

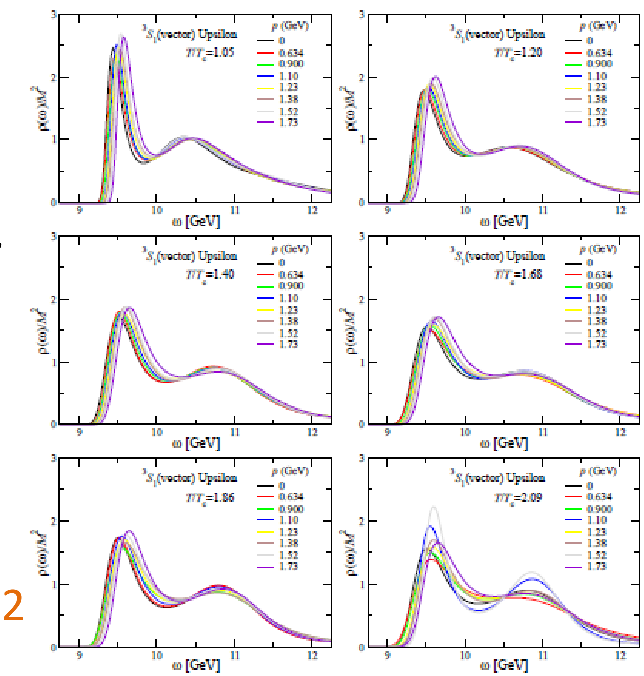
- Charmonia
  - Quenched QCD
  - Both S- and P-wave states are dissociated above ~1.5T_c.

H.-T. Ding *et al.*, PRD 86 (2012) 014509

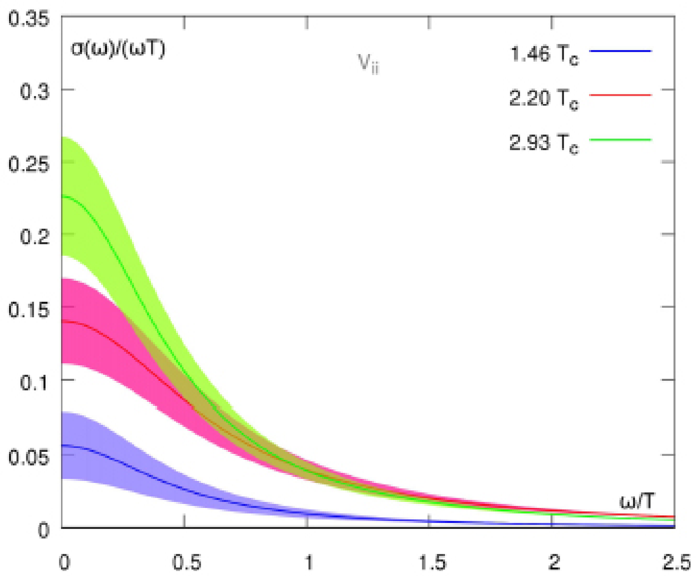


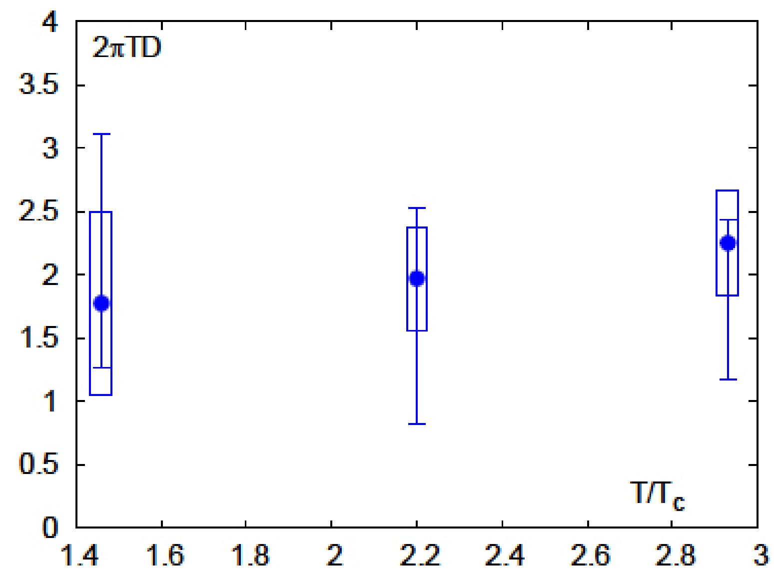
- Bottomonia
  - 2-flavor, nonrelativistic QCD
  - Υ has no temperature dependence up to 2.09T_c.
  - χ_{b0} is sensitive to the presence of thermal medium immediately above T_c.
  - Momentum dependence is effectively temperature independent.

G.Aarts *et al.*, PRL 106 (2011) 061602
G.Aarts *et al.*, JHEP 1303 (2012) 084



Recent lattice studies : diffusion constant





H.-T. Ding *et al.*, PRD 86 (2012) 014509

- Perturbative estimate
  $2\pi DT \approx 71.2$ in LO
  $2\pi DT \approx 8.4$ in NLO

Moore and Teaney, PRD 71 (2005) 064904,
Caron-Hout and Moore, PRL 100 (2008) 052301

- Strong coupling limit
  $2\pi DT \approx 1$

Kovtun, Son and Starinets, JHEP 0310 (2004) 064

Screening mass

Spatial meson correlator

Screening mass

$$G(z) \equiv \int dxdy \int_0^{1/T} d\tau \langle J_H(\tau,\vec{x}) J_H(0,\vec{0}) \rangle \underset{z>>1/T}{\longrightarrow} e^{-\boxed{M_{\rm scr}} z}$$

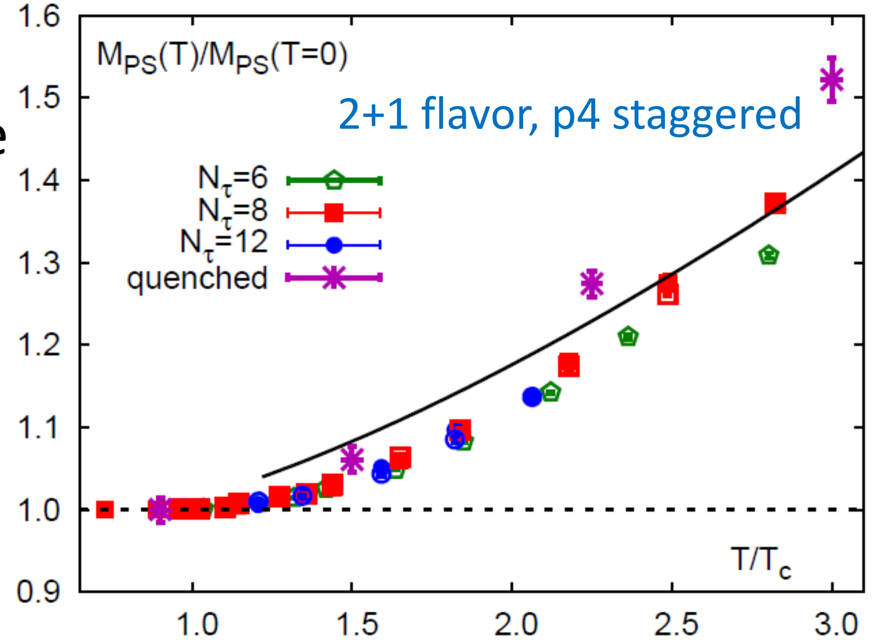
If there is a lowest lying bound state

$$\boxed{M_{\rm scr} = M}$$

High *T* limit (free case)

Quark mass

$$\boxed{M_{\rm scr} = 2\sqrt{(\pi T)^2 + m_q^2}}$$



F. Karsch *et al.*, PRD 85 (2012) 114501

Simulation Setup

- Standard plauette gauge & O(a)-improved Wilson quark actions
- In quenched QCD
- On fine and large isotropic lattices
- 2 different cutoff
- $T = 0.7 - 1.4T_c$
- Both charm & bottom
- Computing meson correlation functions

β	N_σ	N_τ	T/T_c	# confs.
7.192	96	48	0.7	259
		32	1.1	476
		28	1.2	336
		24	1.4	336
7.793	192	96	0.7	60
		48	1.4	91

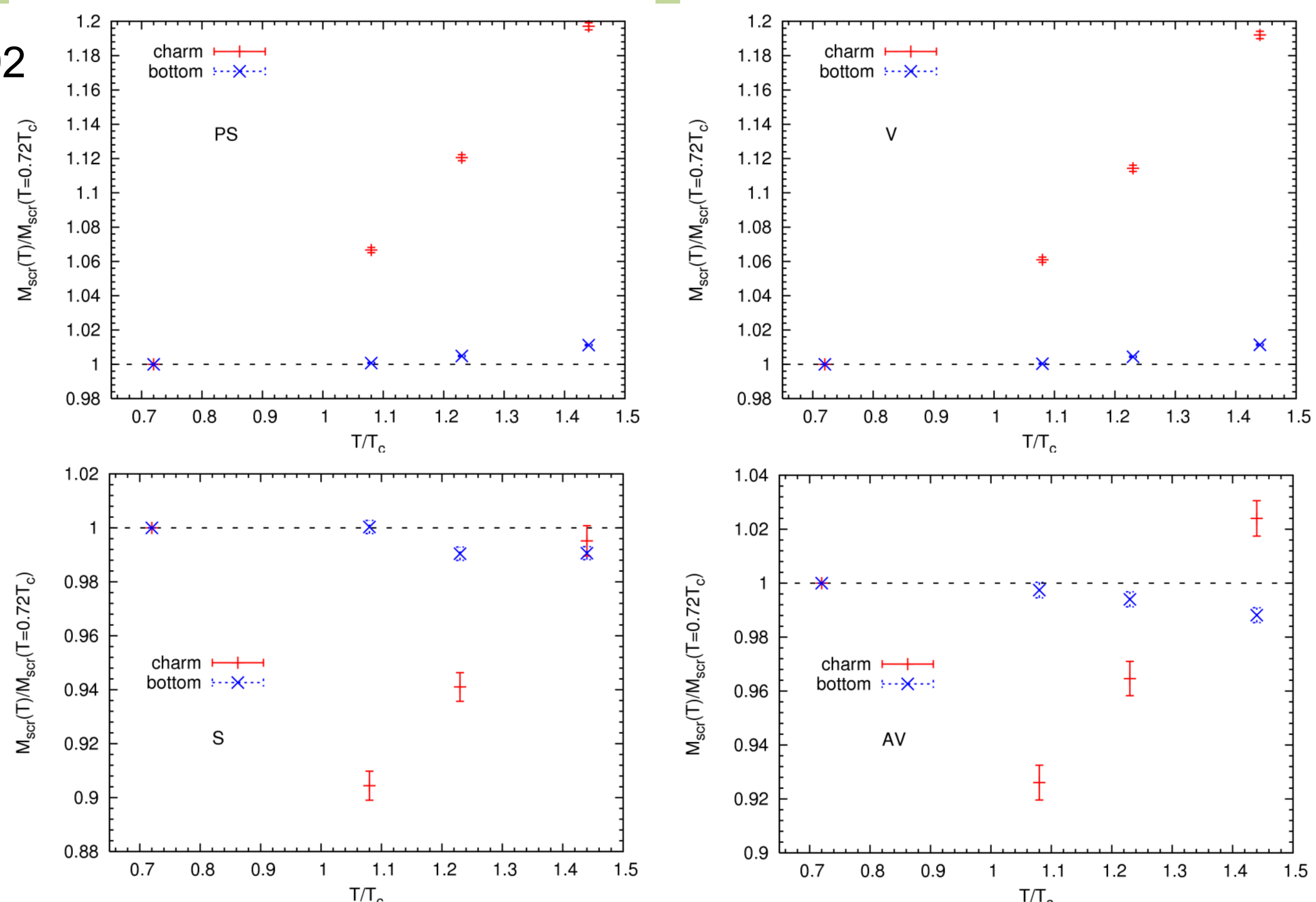
β	a [fm]	a^{-1} [GeV]	κ_{charm}	κ_{bottom}	$m_{J/\Psi}$ [GeV]	m_Υ [GeV]
7.192	0.0190	10.4	0.13194	0.12257	3.105(3)	9.468(3)
7.793	0.00968	20.4	0.13221	0.12798	3.089(6)	9.437(6)

Experimental values: $m_{J/\psi}$ = 3.096.916(11) GeV, m_Υ = 9.46030(26) GeV

J. Beringer *et al*. [PDG], PRD 86 (2012) 010001

Results (1) : Screening mass

β = 7.192



S wave: M_{scr} increases monotonically as increasing temperature.

P wave: M_{scr} has non -monotonic behavior.

Only small temperature dependence for bottom.

Reconstructed correlator

$$G_{\rm rec}(\tau, T; T') \equiv \int_0^\infty d\omega \rho(\omega, T') K(\omega, \tau, T)$$

$$\frac{G(\tau, T)}{G_{\rm rec}(\tau, T; T')}$$ equals to unity at all τ

if the spectral function doesn't vary with temperature

S. Datta *et al.*, PRD 69 (2004) 094507

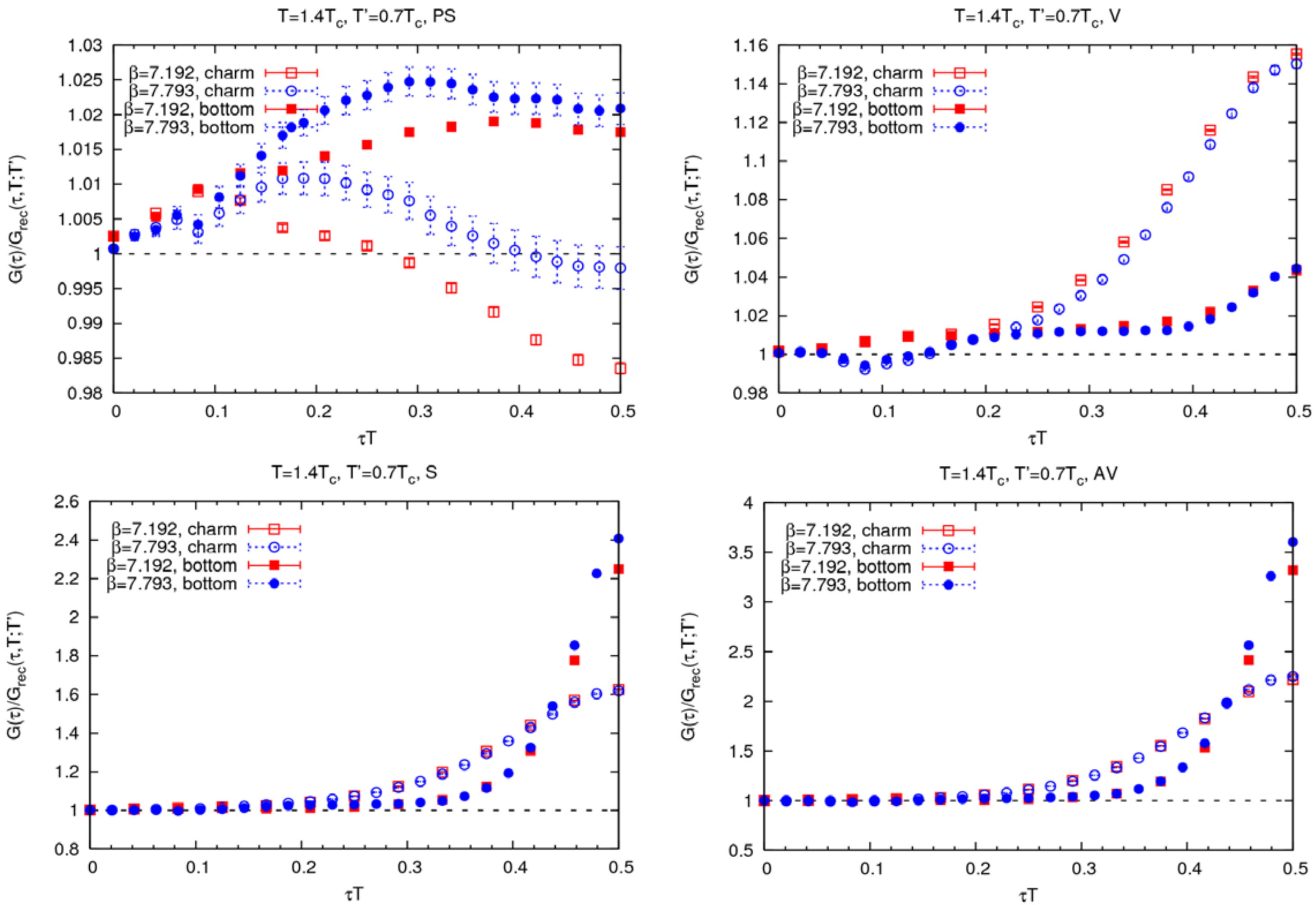
$$\frac{\cosh[\omega(\tau - N_\tau/2)]}{\sinh[\omega N_\tau/2]} = \sum_{\tau'=\tau;\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} \frac{\cosh[\omega(\tau' - N'_\tau/2)]}{\sinh[\omega N'_\tau/2]}$$

$$T = 1/(N_\tau a) \qquad N'_\tau = mN_\tau \qquad m = 1, 2, 3, \cdots$$

$$\boxed{G_{\rm rec}(\tau, T; T') = \sum_{\tau'=\tilde{\tau};\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} G(\tau', T')}$$

H.-T. Ding *et al.*, PRD 86 (2012) 014509

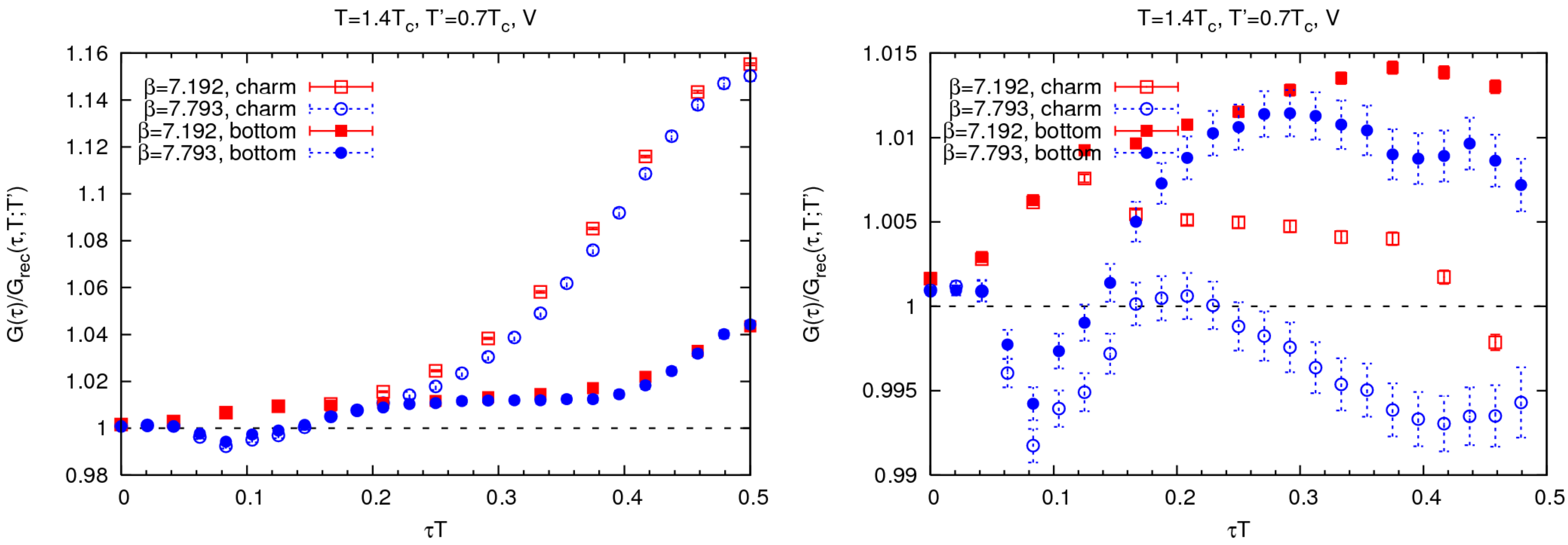
Results (2) : reconstructed correlator



V, S and Av channels have strong modification at large τ, which might be related to the transport peak

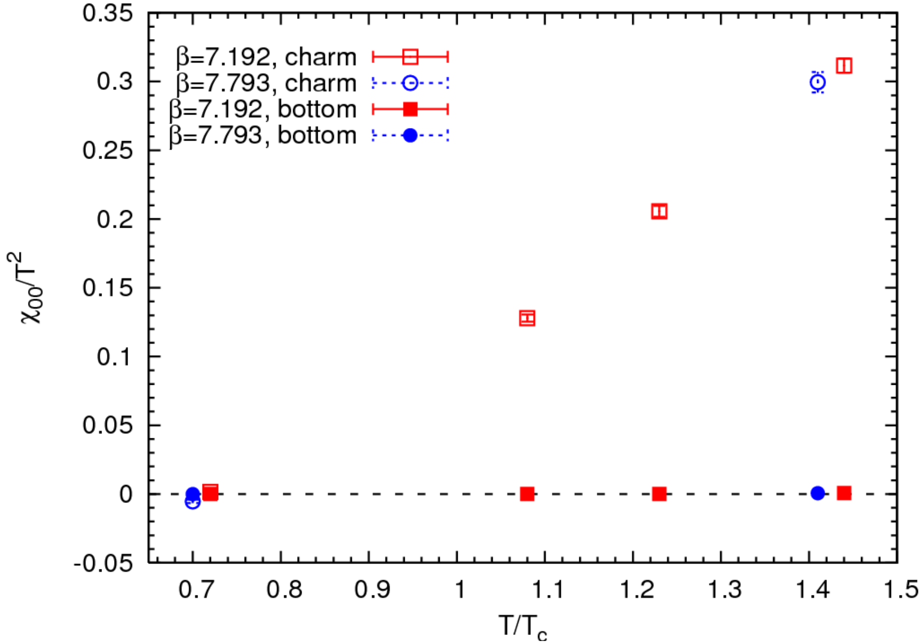
Results (2) : reconstructed correlator

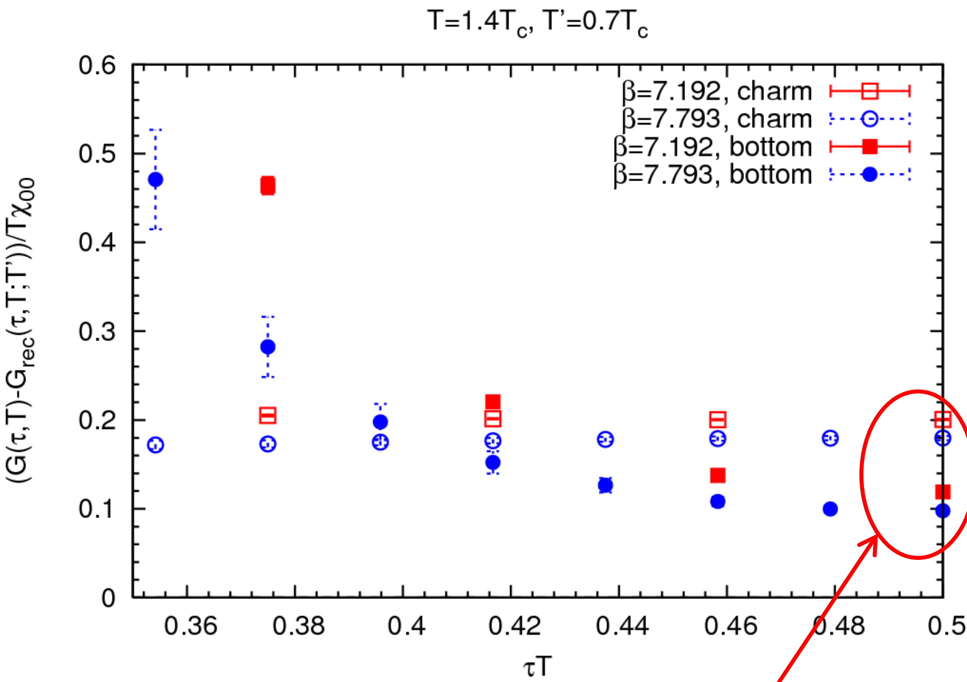
Midpoint subtraction $$\bar{G}(\tau) \equiv G(\tau) - G(1/2T)$$



Most part of the strong enhancement at large τ/a for V channel comes from the zero mode contribution.

Results (3) : heavy quark diffusion constant





χ_{00} : Quark number susceptibility

$\rho_{00}^V(\omega) = 2\pi\chi_{00}\omega\delta(\omega) \Rightarrow G_{00}^V(\tau) = T\chi_{00}$

The contribution from the transport peak should be dominant in $G - G_{rec}$ at $\tau T = ½$.

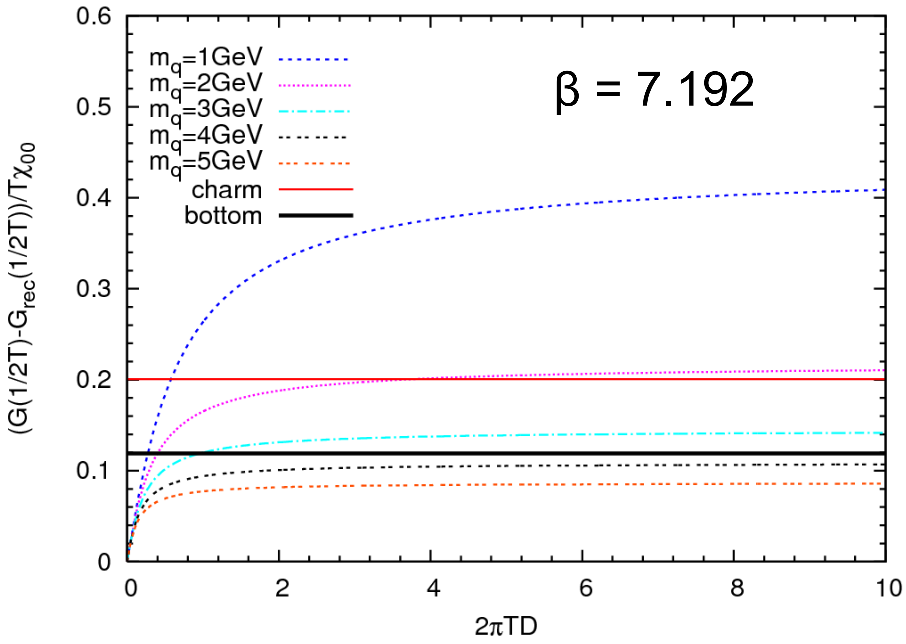
χ_{00} increases as increasing temperature for charm.

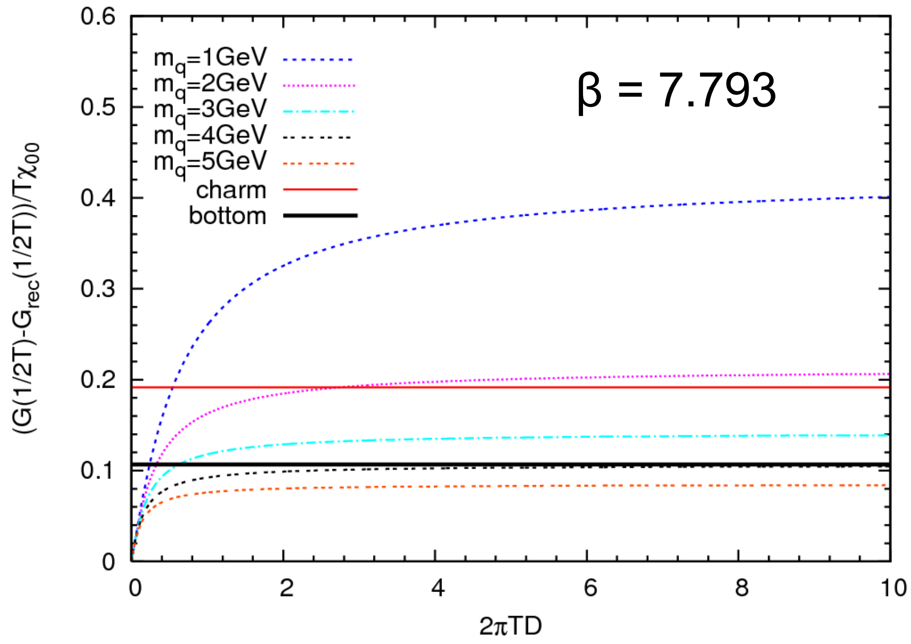
χ_{00} has quite small temperature dependence for bottom.

Results (3) : heavy quark diffusion constant

$$\rho_{ii}^{V}(\omega << T) = 2\chi_{00}\frac{T}{M}\frac{\omega\eta}{\omega^2+\eta^2} \qquad \eta \equiv \frac{T}{MD} \qquad M \equiv m_q a$$

H.-T. Ding *et al.*, PRD 86 (2012) 014509





Charm: 2πTD ≈ 0.6ー4 (β = 7.192), 2πTD ≈ 0.5ー3 (β = 7.793) for m_q = 1ー2 GeV

Bottom: there is no intersection for m_q = 4ー5 GeV

Conclusions

- We calculate meson correlation functions
  - On fine and large isotropic lattices
  - With 2 different cutoff & quark mass for both charm and bottom
- Screening masses
  - different temperature dependence between S and P wave states
  - small temperature dependence for bottomonia
- Meson spectral functions are investigated by using reconstructed correlators
  - V, S and Av channel have strong modification at large τ, which might be related to the transport peak.
  - From the difference between the ordinary and reconstructed correlators, the heavy quark diffusion constant is roughly estimated in the charm case.

Outlook

- Taking continuum limit
- Investigating spectral functions directly
  - Bayesian analysis
- Estimating transport coefficients more accurately.
- Investigating exited states
  - variational analysis

End