Recent progress on in-medium heavy flavor physics from lattice QCD

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Outline

- Introduction
- Spectral properties of quarkonia and open heavy flavor
- Heavy quark transport
- Other approaches
- Conclusion

Why heavy flavor?

- Heavy flavors = charm & bottom

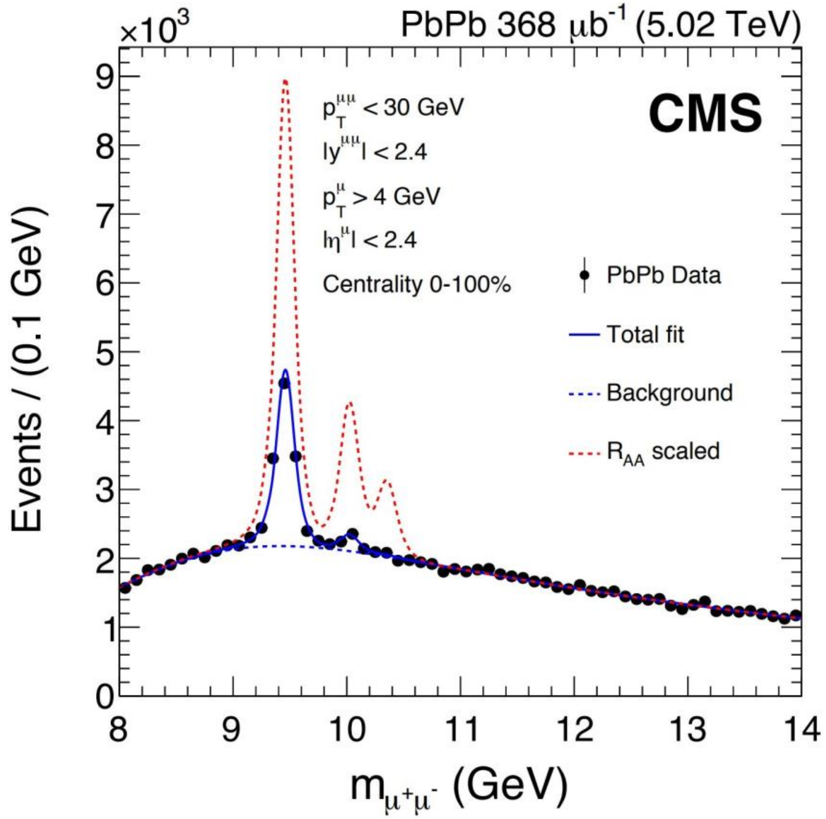
η_c, J/Ψ, χ_c, η_b, Υ, χ_b …

D, B, …

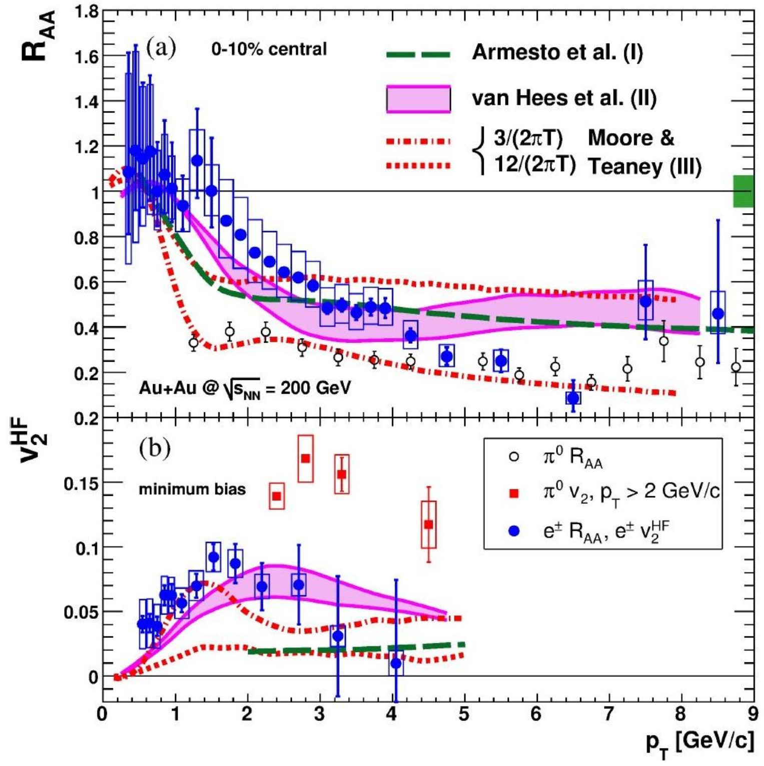
Q = c, b
q = u, d, s

- **Quarkonia ($Q\bar{Q}$)** and **open heavy flavors ($Q\bar{q}$, $q\bar{Q}$)** are important probes to investigate **Quark-Gluon Plasma (QGP)** formed in heavy ion collisions.
  - Produced in the early stage of the collisions: experiencing entire evolution of QGP
  - A signal of QGP formation: color Debye screening in QGP → suppression of quarkonium production T. Matsui and H. Satz, PLB 178 (1986) 416
  - Sequential suppression: different binding energy for different bound state → different melting temperature

What should we understand?



CMS Collaboration@QM2018



PHENIX Collaboration, PRL 98 (2007) 172301

Understanding suppression patterns
→ **dissociation temperatures**

Inputs for transport models
→ **heavy quark diffusion coefficients**

In-medium properties of open/hidden heavy flavors ← All encoded in **spectral functions**

Spectral function

Euclidian (imaginary time) mesonic correlation function

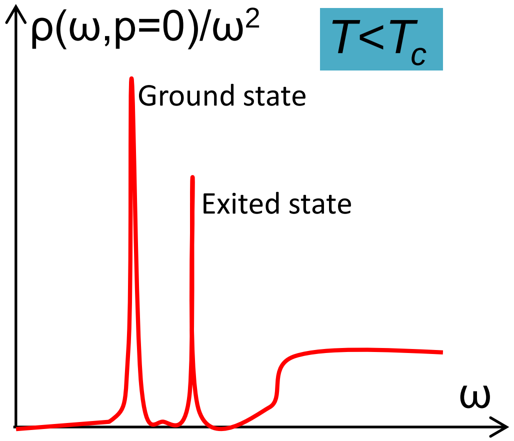
$$G_H(\tau,\vec{p}) \equiv \int d^3x e^{-i\vec{p}\cdot\vec{x}} \langle J_H(\tau,\vec{x}) J_H(0,\vec{0}) \rangle$$

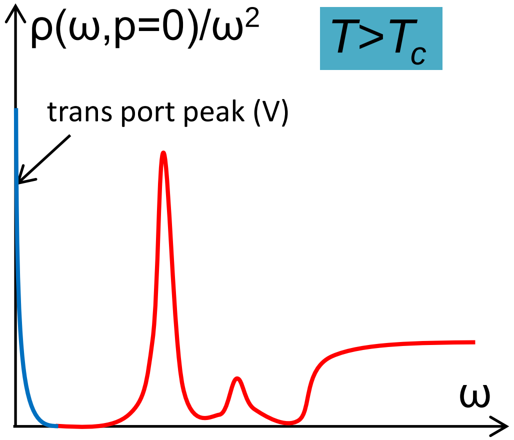
$$= \int_0^\infty \frac{d\omega}{2\pi} \rho_H(\omega,\vec{p}) K(\omega,\tau)$$

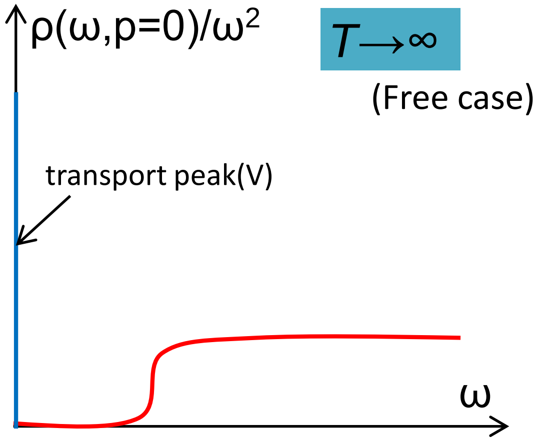
Spectral function

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

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







Heavy quark diffusion coefficient

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

ρ^V_{ii} : Vector spectral function

χ_{00} : Quark number susceptibility

Difficulties on lattice

- **Heavy quark mass m_Q is too heavy!**
  - Basically, fine and large lattices are needed to control lattice artifacts.

- **Obtaining spectral functions: an ill-posted inverse problem!**
  - Number of correlator data points << Number of frequency bins of spectral functions
  - A simple χ^2 fit gives infinite number of possible spectra within statistical uncertainties.

Overcoming difficulties

- **Heavy quark mass m_Q is too heavy!**
  - $m_Q >> \Lambda_{QCD} \rightarrow$ separation of scales (especially for bottom)
  - Effective field theories: **Non-relativistic QCD (NRQCD), potential NRQCD (pNRQCD)**, …

Review: N. Brambilla *et al*., Rev. Mod. Phys. 77 (2005) 1423

- **Obtaining spectral functions: an ill-posted inverse problem!**
  - Adding prior information
  - Bayesian inference: **Maximum Entropy Method (MEM), Bayesian Reconstruction (BR) Method, …**
  - **Phenomenologically motivated (perturbative) modeling of spectral functions**
  - Other approached without spectral functions

Bayesian inference

- Bayes theorem

$$P[A|\bar{G}] = \frac{P[\bar{G}|A]P[A]}{P[\bar{G}]}$$

- Prior probability: prior information

$$P[A] \propto \exp(\alpha S)$$

- Likelihood function: usual χ^2 term

$$P[\bar{G}|A] \propto \exp\left(-\chi^2/2\right)$$

- Posterior probability

$$P[A|\bar{G}] \propto e^{-F}$$

$$\max P[A|\bar{G}] \leftrightarrow \min F \leftrightarrow \frac{\delta F}{\delta A} = 0$$

MEM: Shannon-Jaynes Entropy
→ Limitation of search space

M. Asakawa, T. Hatsuda and Y. Nakahara, Prog.Part.Nucl.Phys. 46 (2001) 459-508

$$S = \int d\omega \left(A - D - A\log\left(\frac{A}{D}\right)\right)$$

BR: new regulator
→ No limitation of search space but possibility of artificial peaks (ringing)

Y. Burnier and A. Rothkopf, PRL 111 (2013) 18, 182003

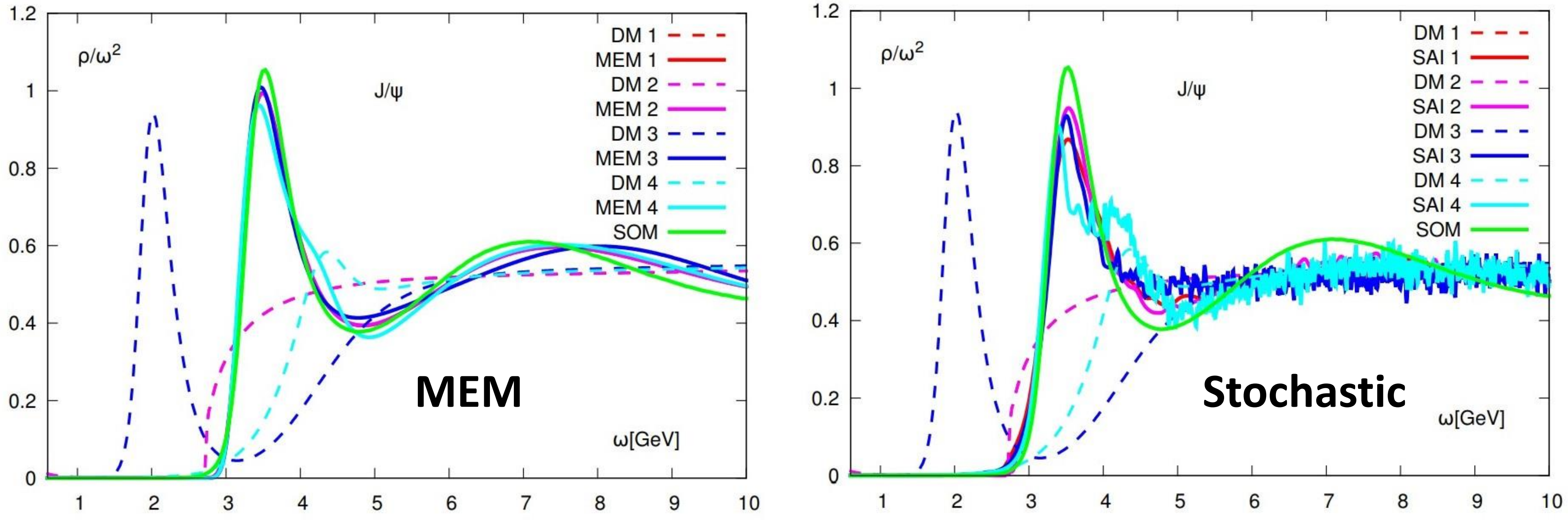
$$S = \int d\omega \left(1 - \frac{A}{D} + \log\left(\frac{A}{D}\right)\right)$$

D: Default model

Another option of Bayesian inference: Stochastic method

- Stochastically finding a spectral image
- Formally equivalent to MEM in a certain limit K.S.D. Beach, arXiv:cond-mat/0403055

J/Ψ@0.75T_c, 128^3x96, Quenched H.-T. Ding, O. Kaczmarek, Swagato Mukherjee, HO and H.-T. Shu, PRD 97 (2018) 9, 094503



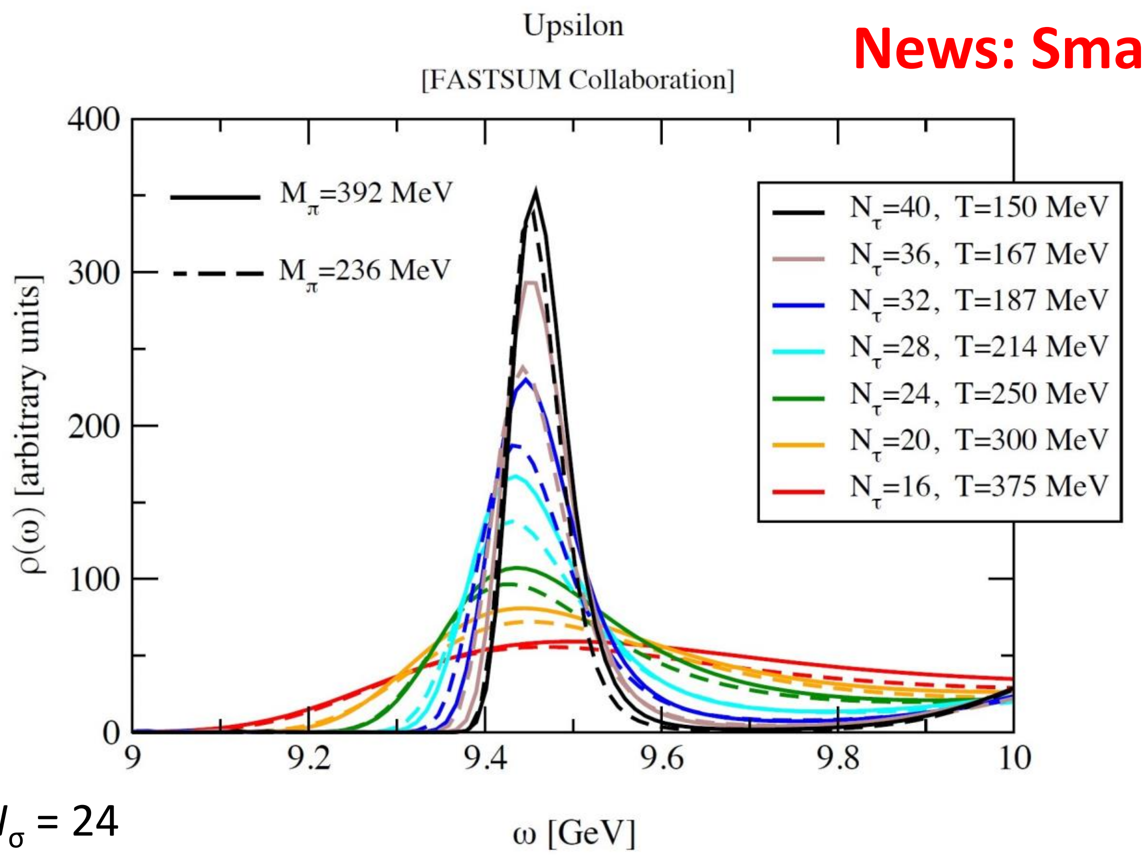
Qualitatively consistent results

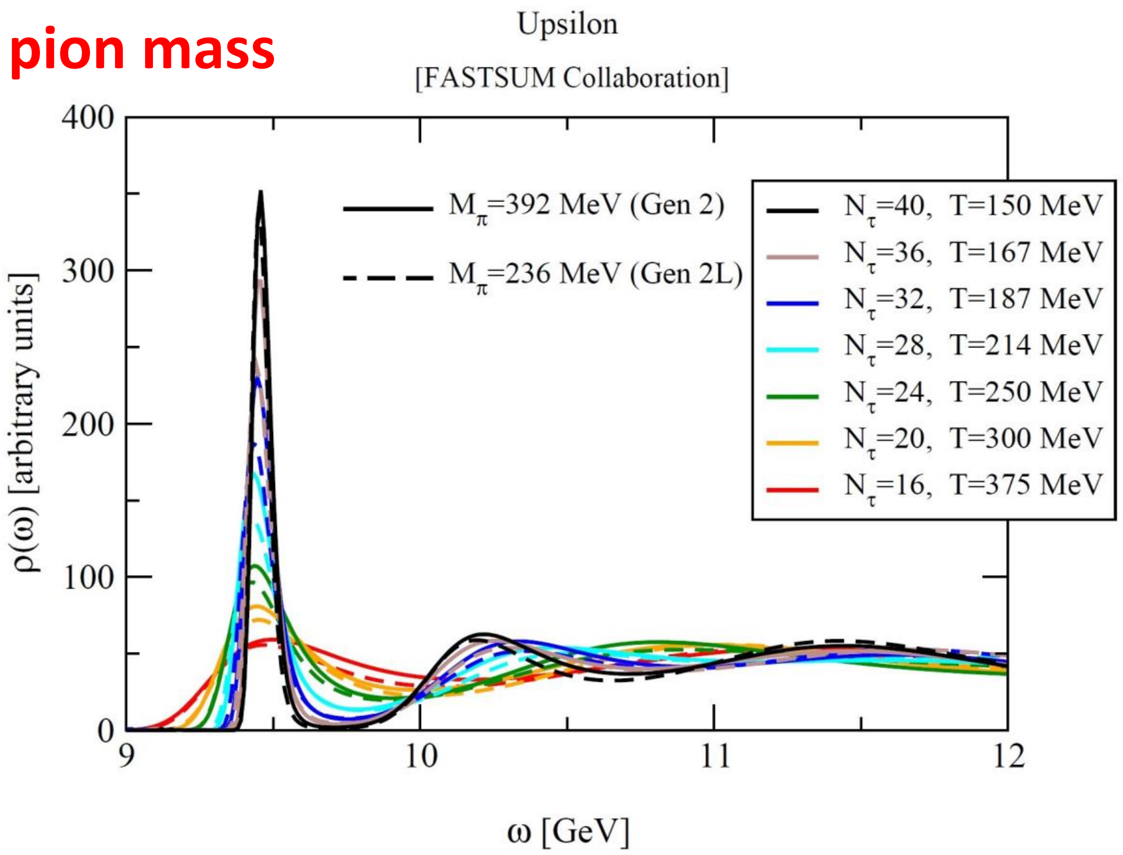
Bottomonium spectral functions

- FASTSUM Collaboration, 2+1 flavor NRQCD, anisotropic a_σ/a_τ = 3.5, MEM

Samuel Offler's talk on Wed. @10:20

News: Smaller pion mass





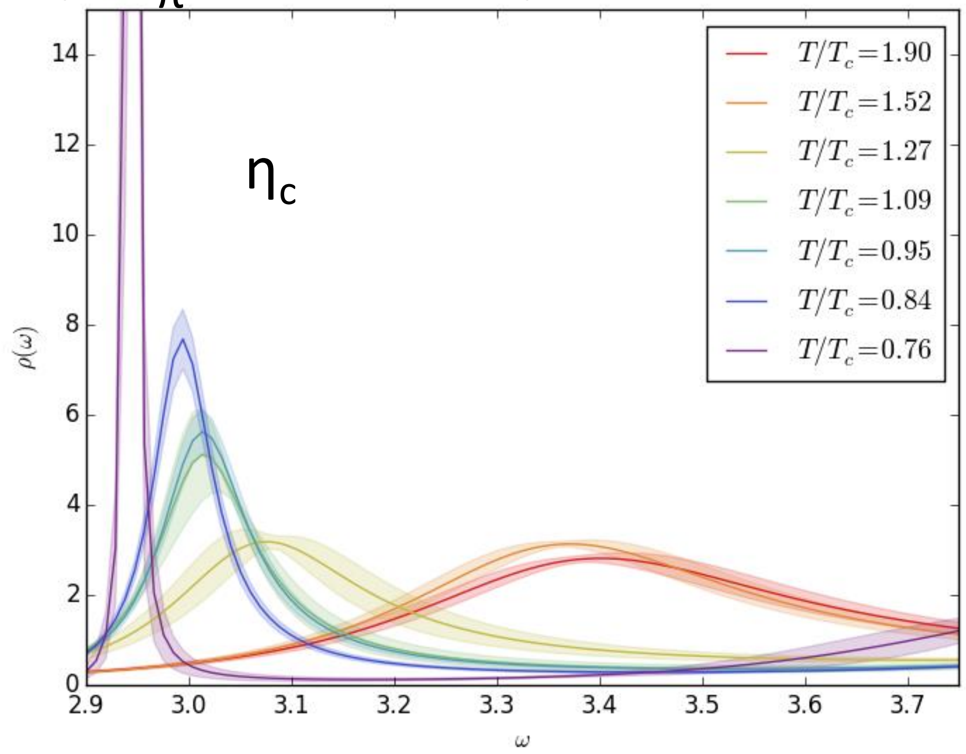
N_σ = 24
a^{-1}_τ = 5.63(4) GeV
$T_c \simeq$ 185 MeV

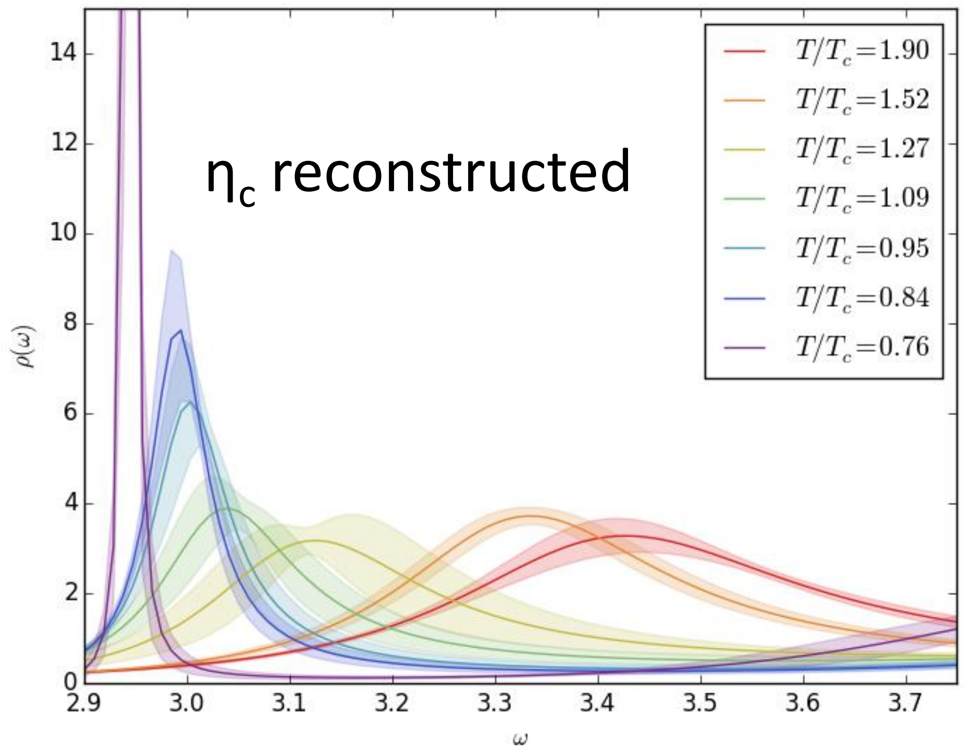
Virtually no effect of pion mass in the Υ spectral function
Survival of Υ(1S) up to the highest temperature (1.9T_c)

Open/hidden charm meson spectral functions

- FASTSUM Generation2 ensemble, 2+1 flavor Clover Wilson, anisotropic a_σ/a_τ = 3.5, m_π = 390 MeV, BR method

R. Quinn *et al*., arXiv:1903.11006 [hep-lat]





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a^{-1}_τ = 5.63(4) GeV
$T_c \simeq$ 185 MeV

Shifting and broadening of the peak in spectral functions from the thermal and reconstructed correlators are consistent with each other up to 1.9T_c.
→ An effect of the limited number of temporal points available

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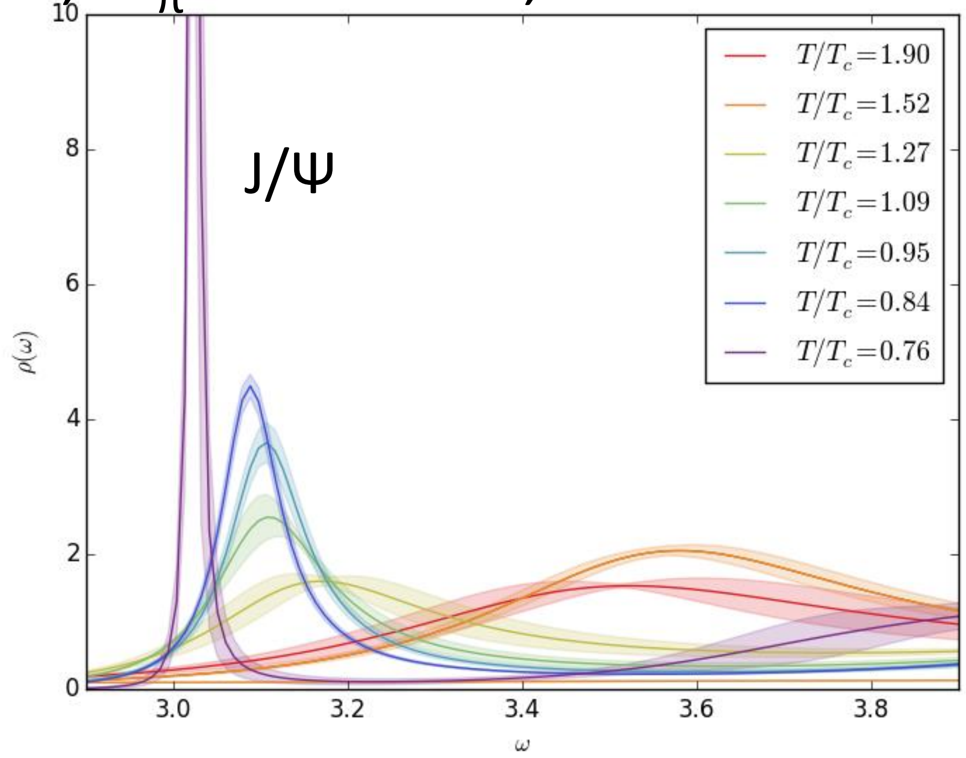

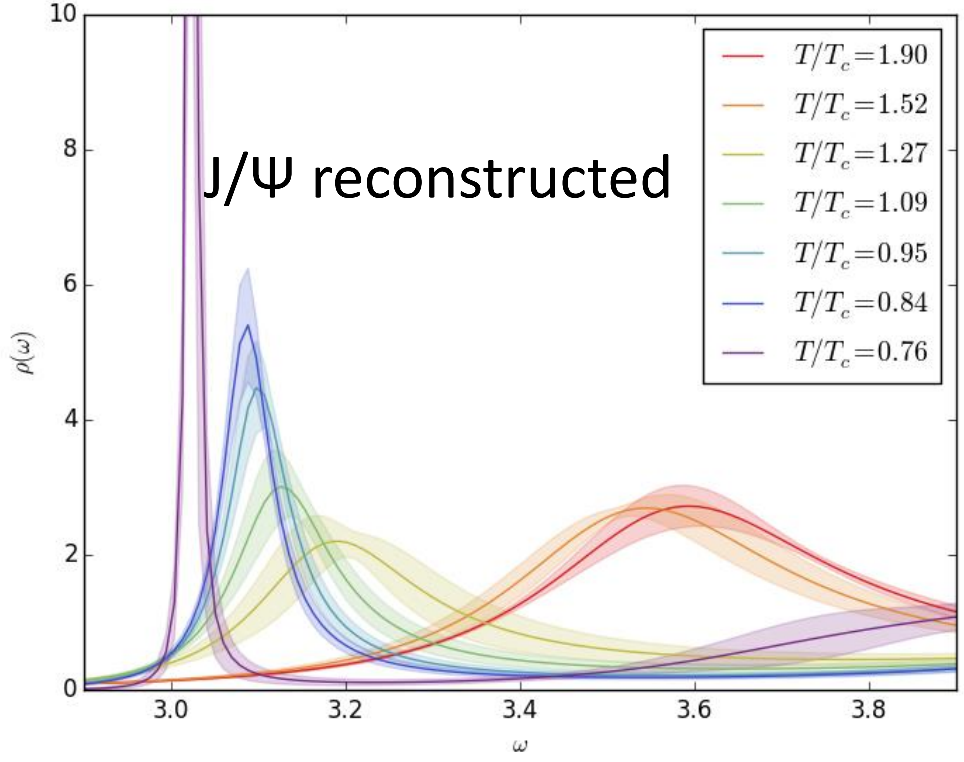

N_σ = 24
a^{-1}_τ = 5.63(4) GeV
$T_c \simeq$ 185 MeV

Shifting and broadening of the peak in spectral functions from the thermal and reconstructed correlators are consistent with each other up to 1.5T_c.
→ An effect of the limited number of temporal points available

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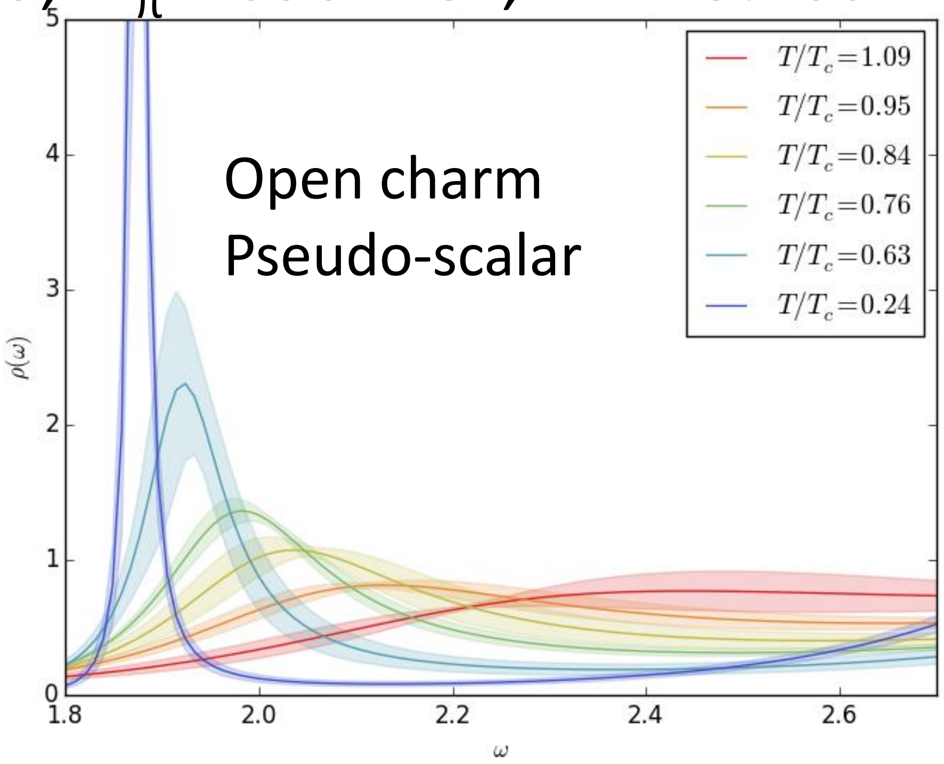

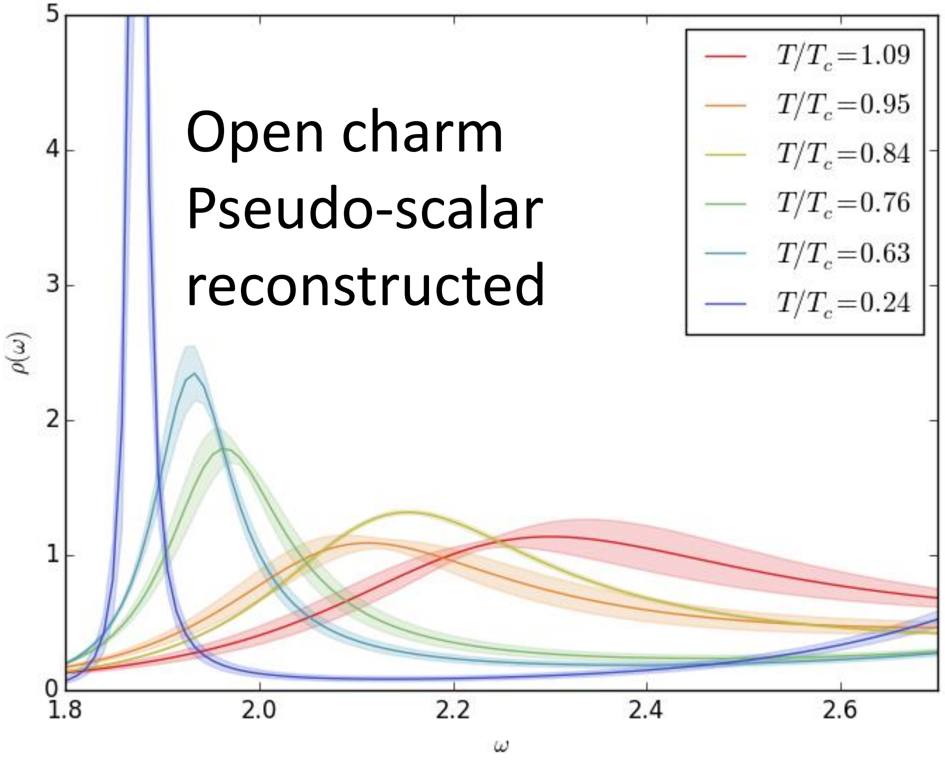

N_σ = 24
a^{-1}_τ = 5.63(4) GeV
$T_c \simeq$ 185 MeV

Spectral functions from the thermal and reconstructed correlators are different already below T_c.
→ No signal of survival of open charm

Fit to a perturbative spectral function

- Quenched QCD, Clover Wilson, continuum extrapolated

Y. Burnier, H. -T. Ding, O. Kaczmarek, A. -L. Kruse, M. Laine, HO, H. Sandmeyer, JHEP11(2017)206

$$\rho^{pert}(\omega) = \underbrace{\rho^{vac}(\omega)}_{\text{Vacuum asymptotics}}\theta(\omega-\omega^{match}) + A^{match}\underbrace{\rho^{NRQCD}(\omega)}_{\text{pNRQCD}}\theta(\omega^{match}-\omega)\underbrace{\Phi(\omega)}_{\text{Suppression}}$$

- High energy ρ^{vac}: Vacuum asymptotics   Burnier, Laine, Eur.Phys.J.C 72 (2012) 1902
- Threshold region ρ^{NRQCD}: pNRQCD   Laine, JHEP 0705:028,2007
- Suppressed at low energy

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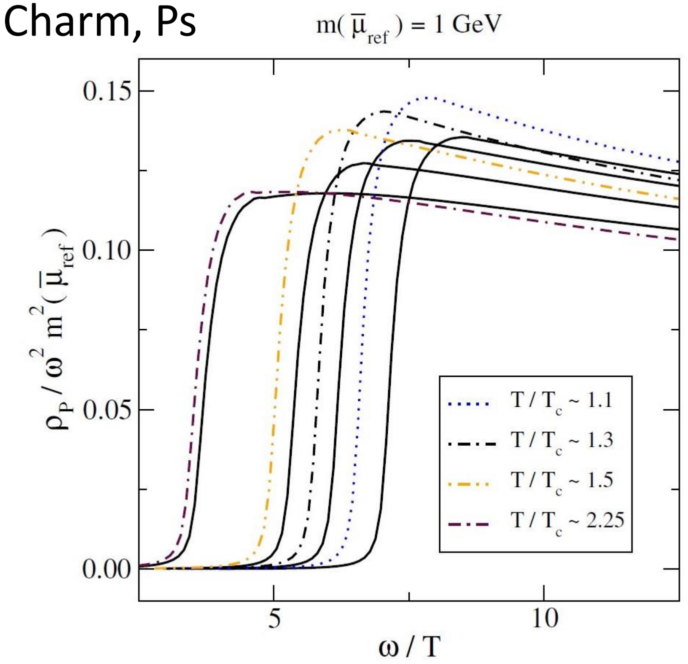
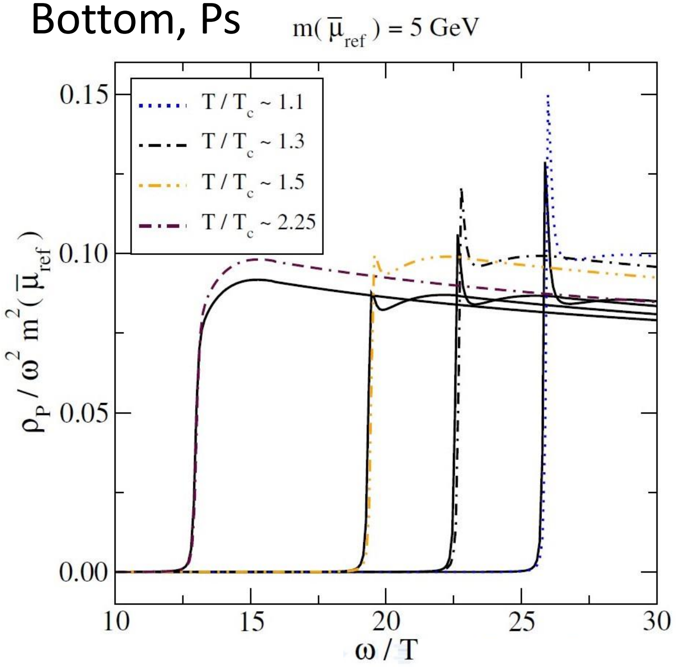
Charm, Ps



Bottom, Ps



$$\rho^{\mathbf{mod}}(\omega) = \mathbf{A}\rho^{\mathbf{pert}}(\omega - \mathbf{B})$$

- **Perturbative spectral function describes lattice data perfectly.**
- **No resonance peak needed for charm.**
- **A resonance peak may be well present for bottom at T ≲ 1.5 Tc.**

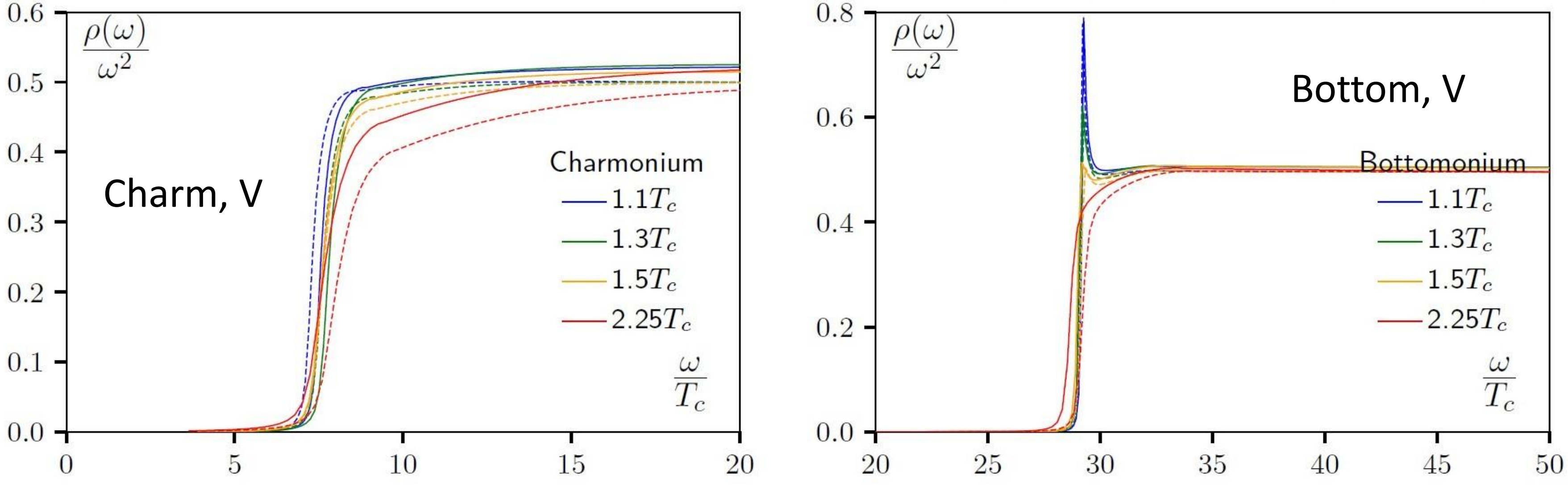
Fit to a perturbative spectral function

- Quenched QCD, Clover Wilson, continuum extrapolated

News: Vector channel & transport

Anna-Lena Kruse's talk on Wed. @9:20

$$\rho^{ii}(\omega) = A\rho^{pert}(\omega - B) + \rho^{trans}(\omega) \qquad \rho^{trans}(\omega) = 3D\chi_q \frac{\omega {\eta_D}^2}{\omega^2 + {\eta_D}^2} \frac{1}{\cosh\left(\frac{\omega}{2\pi T}\right)}$$



- A, B fixed by fit for high ω
- $2\pi TD$ varied from 1 to 9
- η_D: solved

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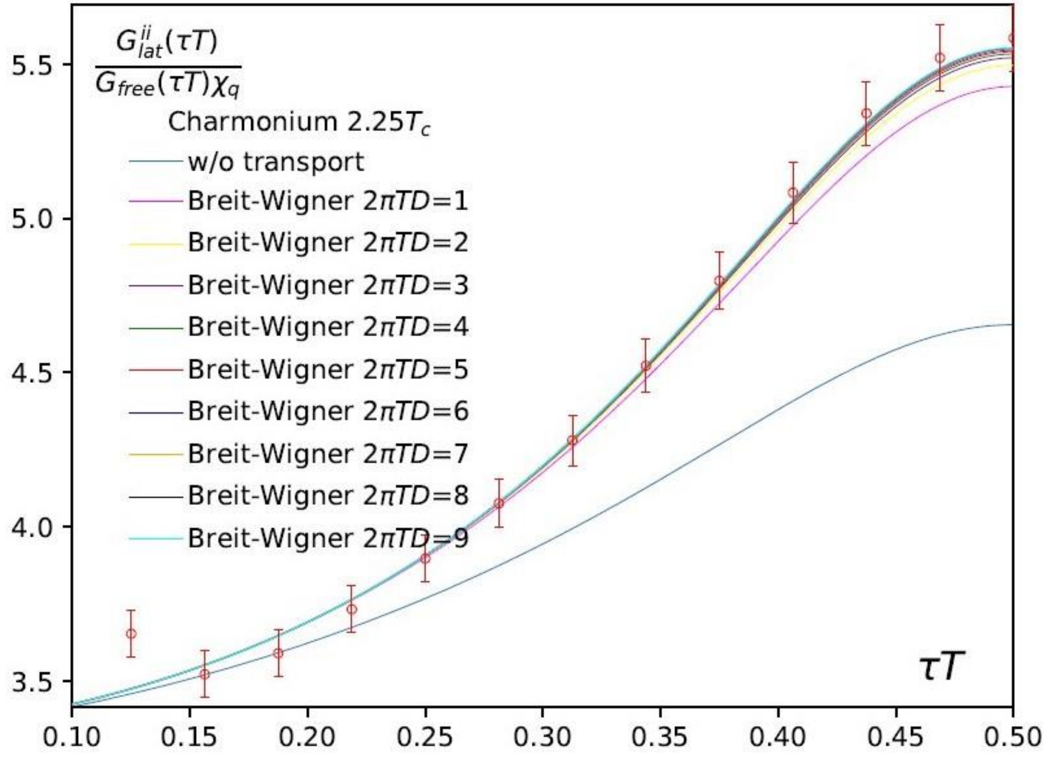


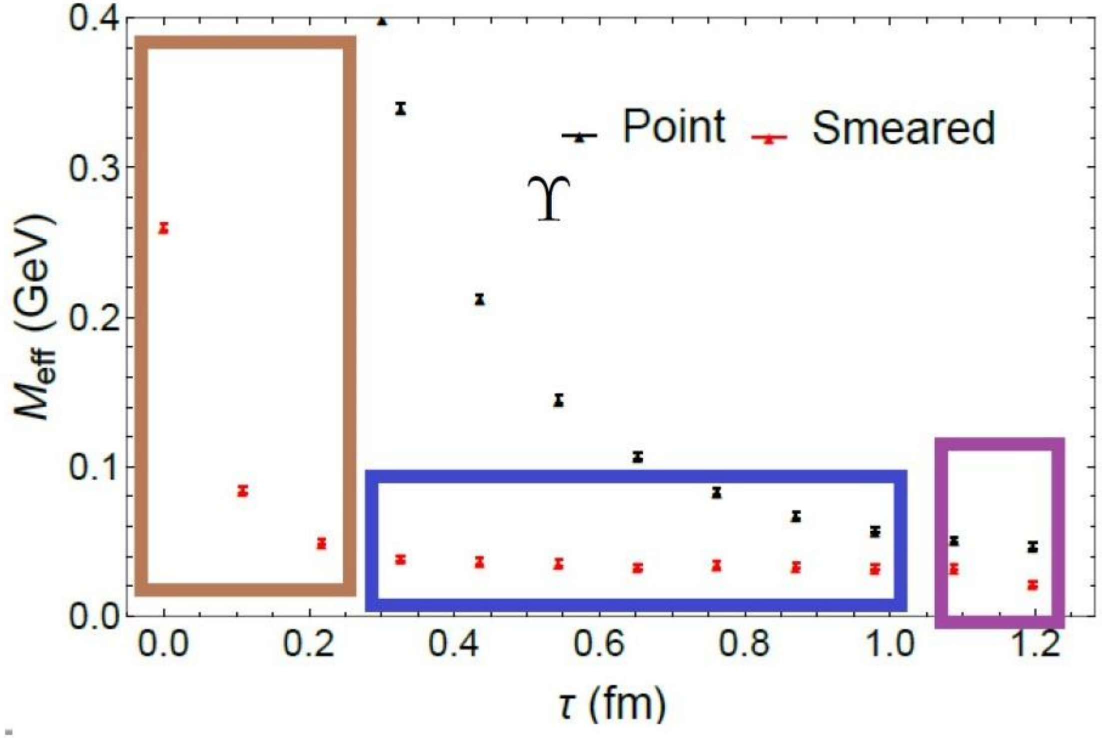
- A, B fixed by fit for high ω
- 2π*TD* varied from 1 to 9
- η_D: solved

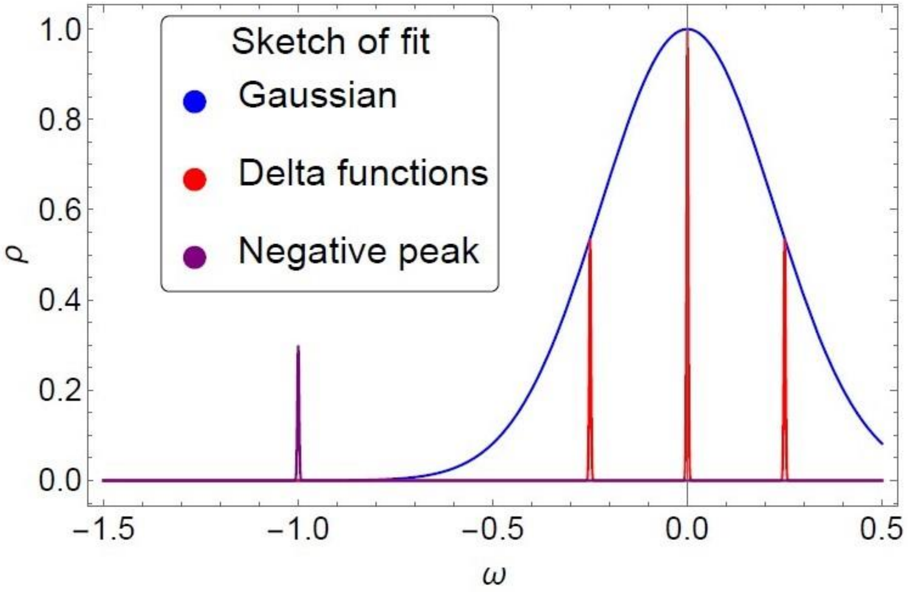
Possible lower bound at 2π*TD* = 2

Mass shift and width of SPF from smeared correlators

- HoTQCD ensembles, $N_\sigma = 48$, $N_\tau = 12$, $m_\pi = 160$ MeV, physical Kaon mass, NRQCD

Rasmus Larsen's poster





- Fit data with ansatz for spectral function $\rho(\omega)$ sketched in right plot
- Will subtract $T = 0$ continuum from finite temperature correlator

$$C_{sub,T>0}(\tau) \quad = \quad C_{T>0}(\tau) - C_{T=0}(\tau) + A\exp(-m_{T=0}\tau)$$

Mass shift and width of SPF from smeared correlators

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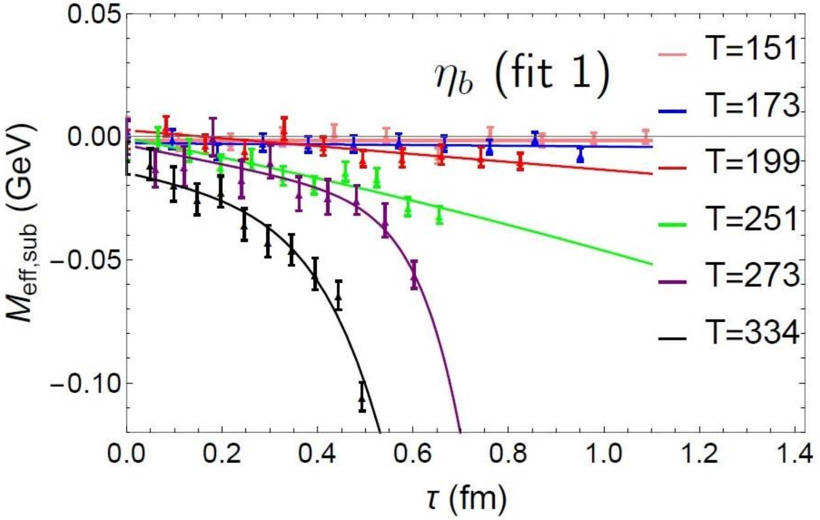
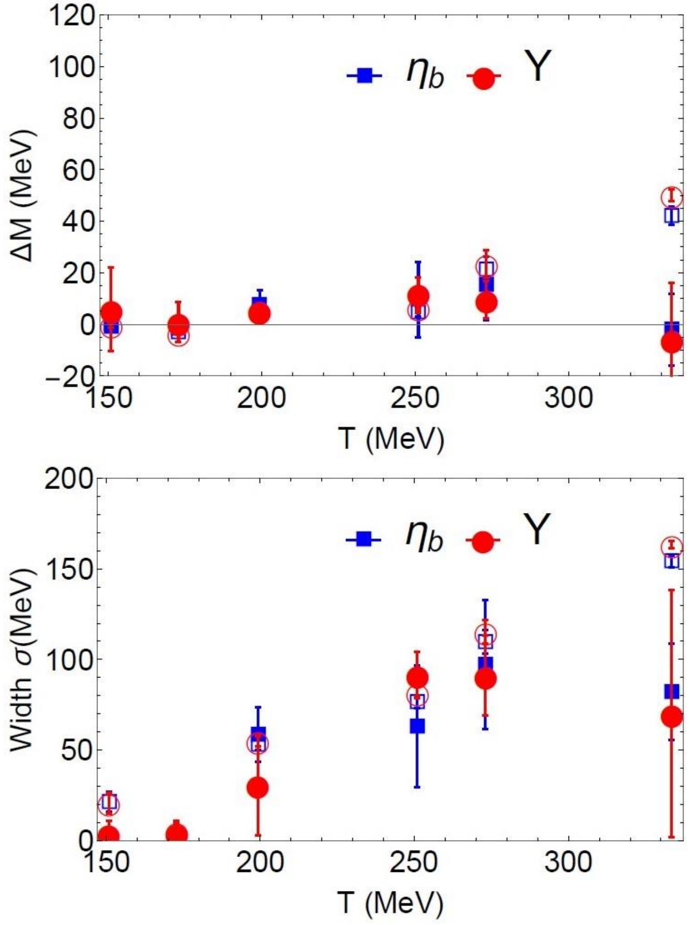
Rasmus Larsen's poster

- Zero temperature continuum subtracted
- (fit 1 filled) Main peak + small negative peak
- (fit 2 empty) Main peak and last 2 points removed



- Results for Υ and η_b very similar



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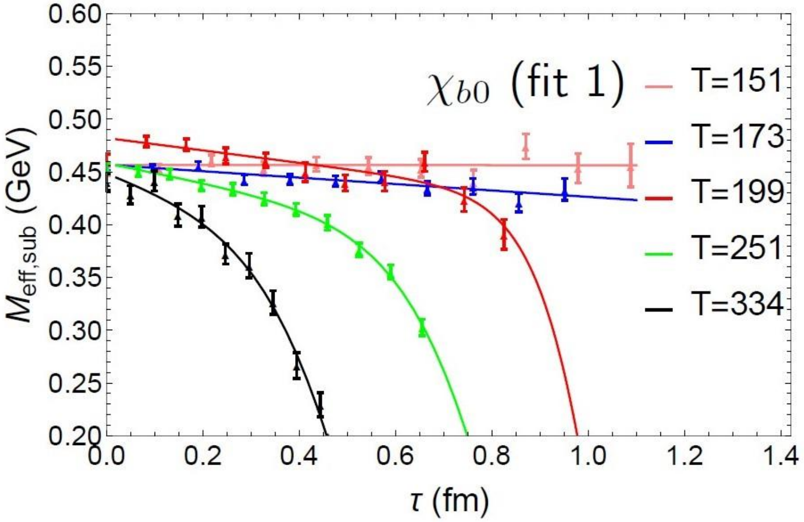
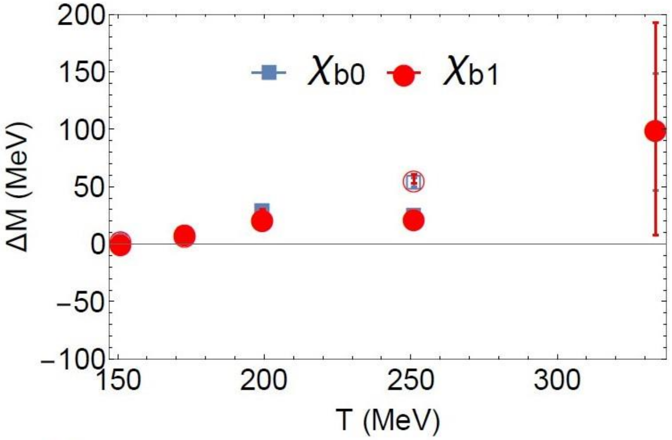
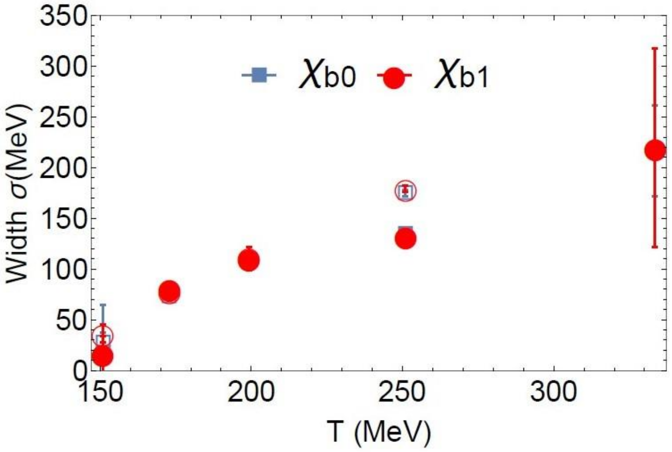


- Results for χ_{b0} and χ_{b1} very similar





The other related talks/posters in this conference

- Real-Time-Evolution of Heavy-Quarkonium Bound States
  Alexander Lehmann's talk on Wed. @11:10
- Euclidean correlation functions for transport coefficients under gradient flow
  Hai-Tao Shu's talk on Wed. @11:30
- Heavy quark diffusion coefficient from lattice
  Viljami Leino's talk on Wed. @11:50
- Non-perturbative study of heavy quark anti-quark potential at finite temperature
  Dibyendu Bala's talk on Fri. @14:40
- Thermal Quarkonium Mass Shift from Euclidean Correlators
  Alexander Maximilian Eller's poster
- Quarkonium suppression in non-equilibrium quark-gluon plasma
  Zhandos Moldabekov's poster

Conclusions

- Quarkonia and open heavy flavors are important probes to investigate QGP.
- There are some difficulties for heavy flavor calculations on the lattice.
- Effective field theories are useful tool for bottom.
- There are a few approaches to reconstruct spectral functions.
- Full QCD studies for spectral functions of charmonia, bottomonia as well as open charm mesons have been already done.
- Continuum extrapolated quarkonia spectral functions have been studied with quenched QCD and perturbative models.
- A new kind of approach with smeared correlators to investigate quarkonium spectral function have been shown.
- There are variety of other approaches for heavy flavor physics.