DFG Deutsche Forschungsgemeinschaft

ISOQUANT SFB1225

In-medium heavy quarkonium spectral properties from lattice QCD effective field theories

Alexander Rothkopf
Institute for Theoretical Physics
Heidelberg University

in collaboration with **S. Kim (Sejong-U.)** and **P. Petreczky (BNL)**

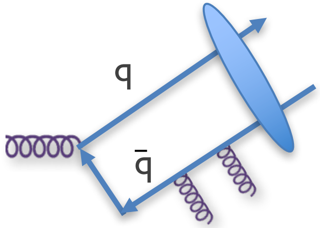
References:

with S.Kim and P. Petreczky PRD91 (2015) 054511, NPA956 (2016) 713
arXiv:1704.05221

INTERNATIONAL MINI-WORKSHOP ON "LATTICE AND FUNCTIONAL TECHNIQUES FOR EXPLORATION OF PHASE STRUCTURE AND TRANSPORT PROPERTIES IN QUANTUM CHROMODYNAMICS" – JINR, DUBNA, RUSSIAN FEDERATION – JULY 10TH 2017

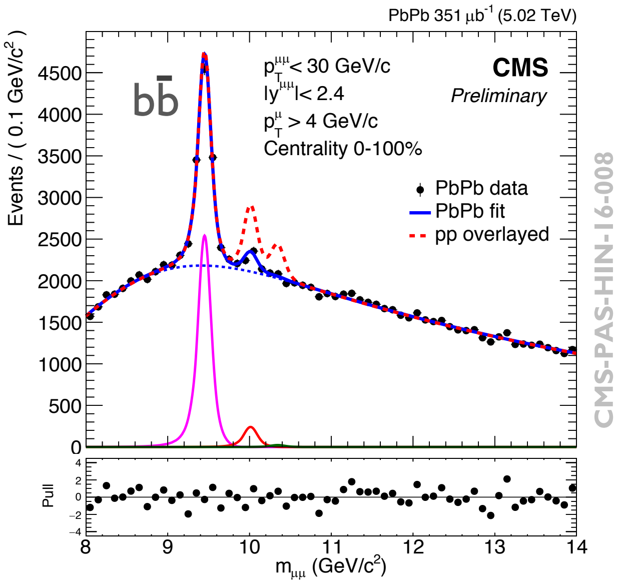
Motivation: Heavy-Ion Collisions

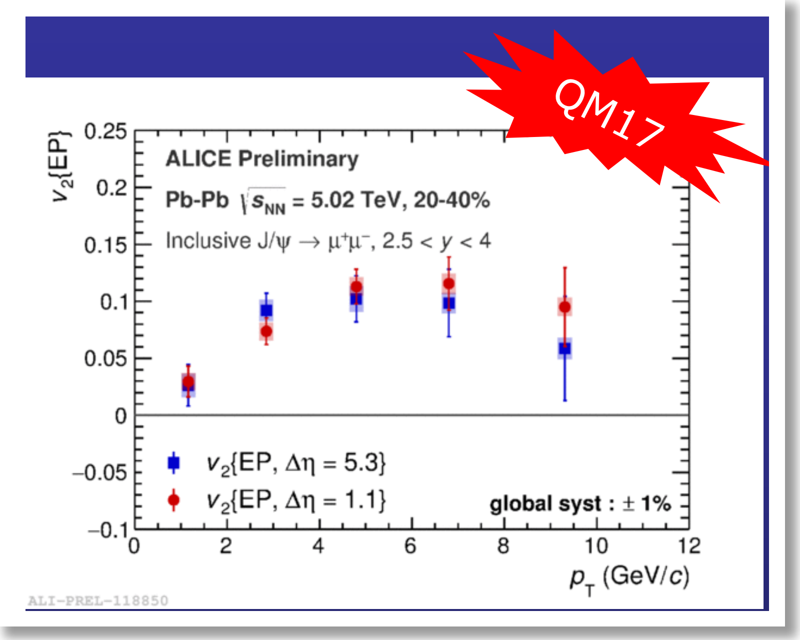
- Hard probes: susceptible to medium but distinguishable from it $Q_{probe} > T_{med}$



Bound states of $c\bar{c}$ or $b\bar{b}$: **Heavy quarkonium** $M_Q > T_{med}$

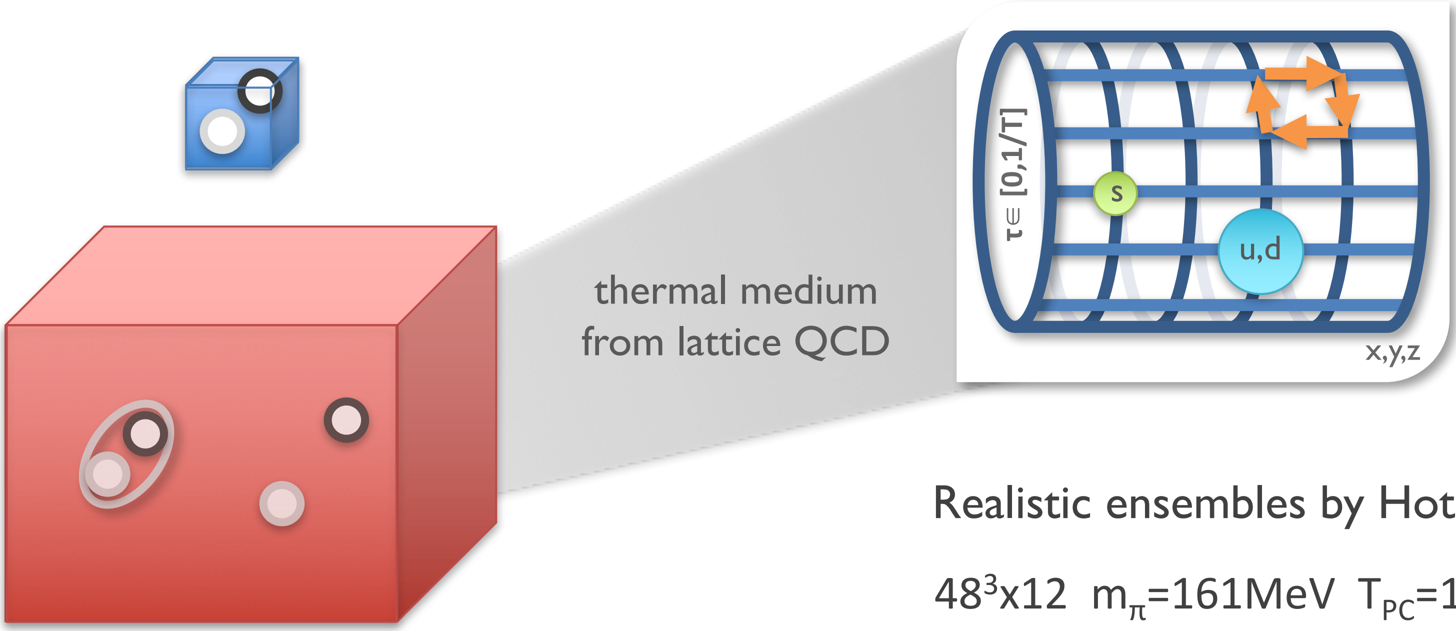
In vacuum: m^{Υ}=9.460GeV, Γ^{Υ} = 54(1)keV; $m^{J/\psi}$=3.096 GeV, $\Gamma^{J/\psi}$ = 93(3)keV





- Goal: First principles insight into heavy quarkonium in heavy-ion collisions

A first-principles scenario



thermal medium
from lattice QCD

T. Matsui and H. Satz: Phys.Lett. B178 (1986) 416

Kinetically equilibrated heavy quarks

presence of in-medium bound eigenstates?

answered by inspecting spectral functions

Realistic ensembles by HotQCD

48^3x12 m_π=161MeV T_{PC}=159MeV

Fixed box: β=6.664-7.825

T = [140 – 407] MeV

T=0 configs for calibration 48^3x48,64

HotQCD PRD85 (2012) 054503, PRD90 (2014) 094503

Heavy Quarks on the Lattice

- Effective field theory from scale separation: $\frac{\Lambda_{QCD}}{m_Q} \ll 1, \quad \frac{T}{m_Q} \ll 1, \quad \frac{\mathbf{p}}{m_Q} \ll 1$

Brambilla et. al.
Rev.Mod.Phys. 77 (2005) 1423

Relativistic thermal field theory

QCD	**NRQCD**
Dirac fields	**Pauli fields**
$\bar{Q}(x), Q(x)$	$\chi^\dagger(x), \chi(x)$ $\xi^\dagger(x), \xi(x)$

$\bar{q}(x), q(x), A^\mu(x)$

$$L_{NRQCD} = \chi^\dagger\left(iD_t + \frac{D_i^2}{2M_Q} + \dots\right)\chi + \xi^\dagger(\dots)\xi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{q}(\dots)q$$

- Individual Q or anti-Q in a medium background: Initial value problem $G(\tau) = \langle \chi(\tau)\chi^\dagger(0)\rangle$

$$G(\mathbf{x}, \tau + a) = U_4^\dagger(\mathbf{x}, \tau)\left(1 - \frac{\mathbf{p}_{lat}^2}{4M_Q a n} + \dots\right)^n G(\mathbf{x}, \tau)$$

Davies, Thacker Phys.Rev. D45 (1992)

adaptive discretization in time with Lepage parameter n

- $^3S_1$ (Υ) and $^3P_1$ (χ_{b1}) channel correlators $D(\tau)$ from products of heavy quark propagators $G(\tau)$

$$D(\tau) = \sum_{\mathbf{x}} \langle O(\mathbf{x}, \tau) G_{\mathbf{x}\tau} O^\dagger(\mathbf{x}_0, \tau_0) G^\dagger_{\mathbf{x}\tau}\rangle_{med} \qquad O(^3S_1; x, \tau) = \sigma_i, \quad O(^3P_1; x, \tau) = \overleftrightarrow{\Delta}_i \sigma_j - \overleftrightarrow{\Delta}_j \sigma_i$$

Thacker, Lepage Phys.Rev. D43 (1991)

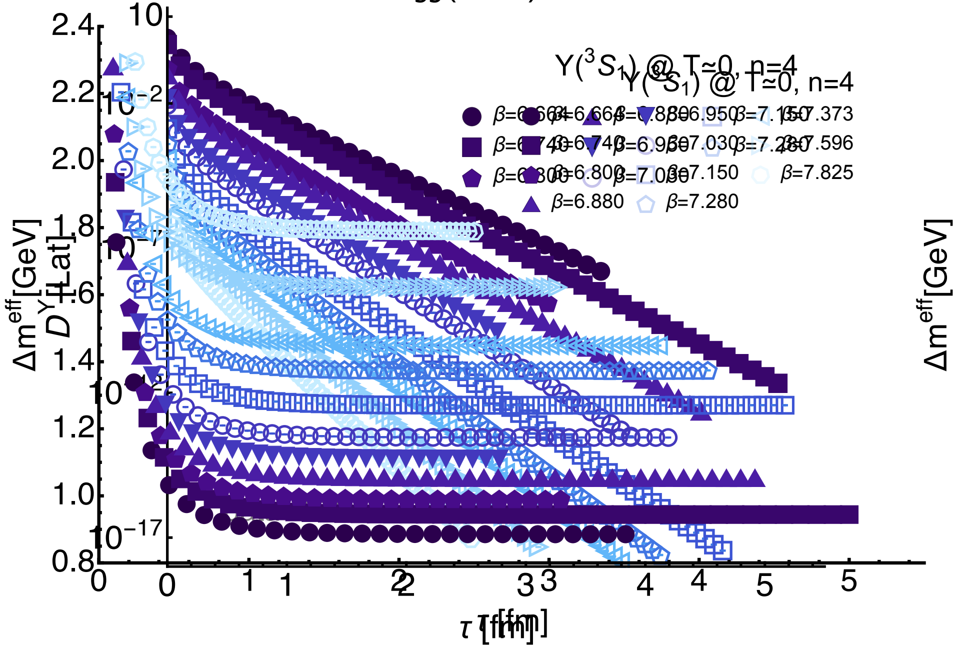
- Applicability of NRQCD differs for heavier and lighter flavors (bb: n=4, cc:n=8)

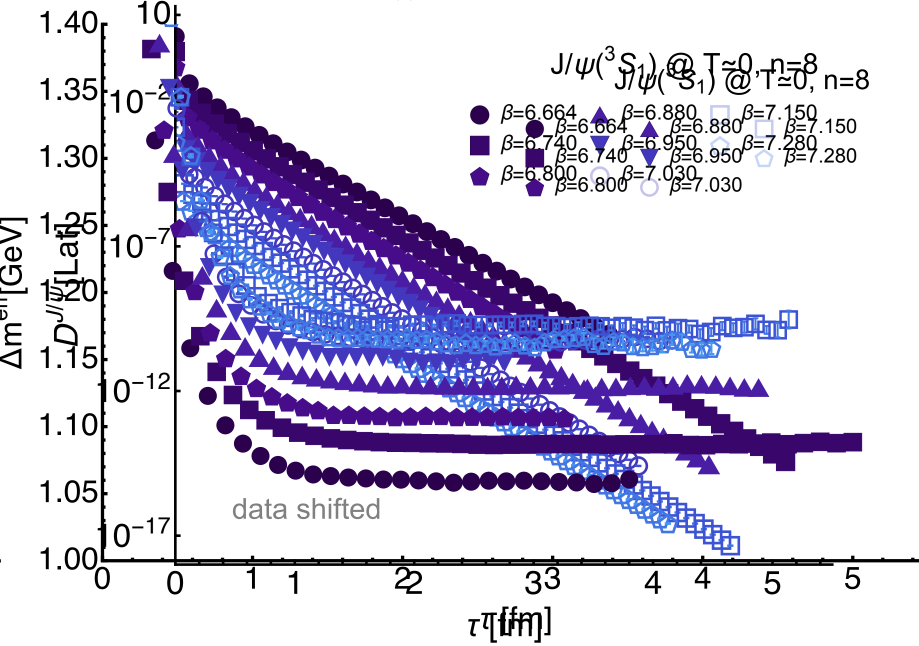
$M_b a$= [2.759 – 0.954] - T= [140 – 407] MeV $M_c a$= [0.757 – 0.42] - T= [140 – 251] MeV

T=0 correlators in NRQCD

$N_{bb}^{meas}(T=0)=400$

$N_{cc}^{meas}(T=0)=200$





S.Kim, P.Petreczky, A.R. in preparation

- For both Bottomonium and Charmonium clear ground state signal at T=0

Accessing spectral functions

- Inversion of Laplace transform required to obtain spectra from correlators

$$D(\tau) = \int_{-2M_Q}^{\infty} d\omega\, e^{-\tau\omega}\, \rho(\omega) \qquad D_i = \sum_{l=1}^{N_\omega} \exp[-\omega_l \tau_i]\, \rho_l\, \Delta\omega_l$$

1. N_ω parameters ρ_l >> N_τ datapoints
2. data D_i has finite precision

- Give meaning to problem by incorporating prior knowledge: Bayesian approach

M. Jarrell, J. Gubernatis, Physics Reports 269 (3) (1996)

  - Bayes theorem: Regularize the naïve χ^2 functional P[D|ρ] through a prior P[ρ|I]

$$P[\rho|D,I] \propto P[D|\rho]\; P[\rho|I]$$

  - New prior enforces: ρ positive definite, smoothness of ρ, result independent of units

$$P[\rho|I] \propto e^S \qquad S = \alpha \sum_{l=1}^{N_\omega} \Delta\omega_l \left(1 - \frac{\rho_l}{m_l} + \log\left[\frac{\rho_l}{m_l}\right]\right)$$

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

  - **Different from Maximum Entropy Method**: S not entropy, no more flat directions

$$\frac{\delta}{\delta\rho} P[\rho|D,I]\Big|_{\rho=\rho^{BR}} = 0$$

An improved Bayesian strategy

- First lever: improve the data on which inverse problem is based

$$D(\tau) = \int_{-2M_Q}^{\infty} d\omega e^{-\tau\omega} \rho(\omega) \quad \xleftrightarrow{\text{Fourier}} \quad D(\mu) = \int_0^{\infty} d\omega \frac{2\omega}{\omega^2+\mu^2} \rho(\omega)$$

  - **Improvement:** incorporate both Euclidean and imaginary frequency data in unfolding

- Second lever: develop improved regulators to better assess systematics

Standard BR method (BRFT)

$$S_{BR} = \alpha \int d\omega \Big(1 - \frac{\rho}{m} + \log\Big[\frac{\rho}{m}\Big]\Big)$$

- Resolves narrow peaked structures with high accuracy
- Ringing in broad structures if reconstructed from small # of datapoints

„high gain – high noise“

Y. Burnier, A.R. PRL 111 (2013) 182003

New low ringing BR method

$$S_{BR}^{lr} = \alpha \int d\omega \Big(\Big(\frac{\partial\rho}{\partial\omega}\Big)^2 + 1 - \frac{\rho}{m} + \log\Big[\frac{\rho}{m}\Big] \Big)$$

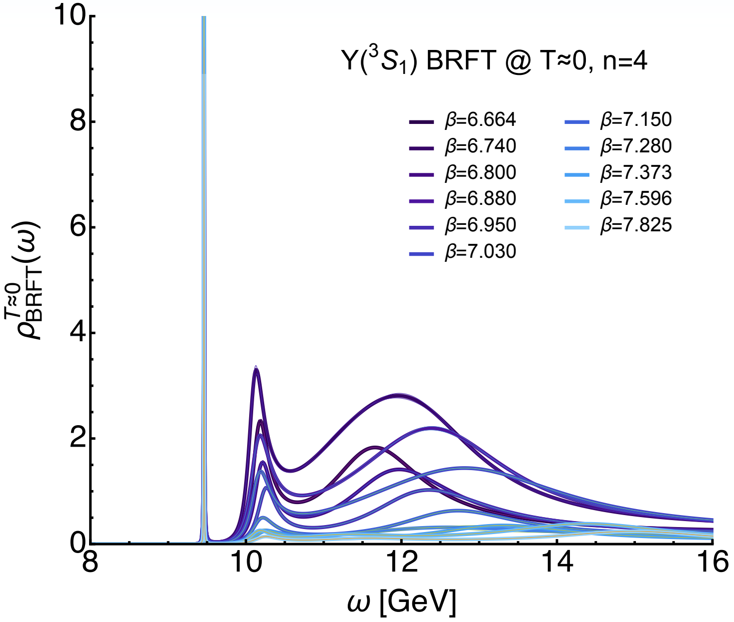
- Introduces penalty on arc length of reconstruction $(dL/dw)^2=1+(d\rho/dw)^2$
- Efficiently removes ringing but may lead to overestimated peak widths

„low gain – low noise“

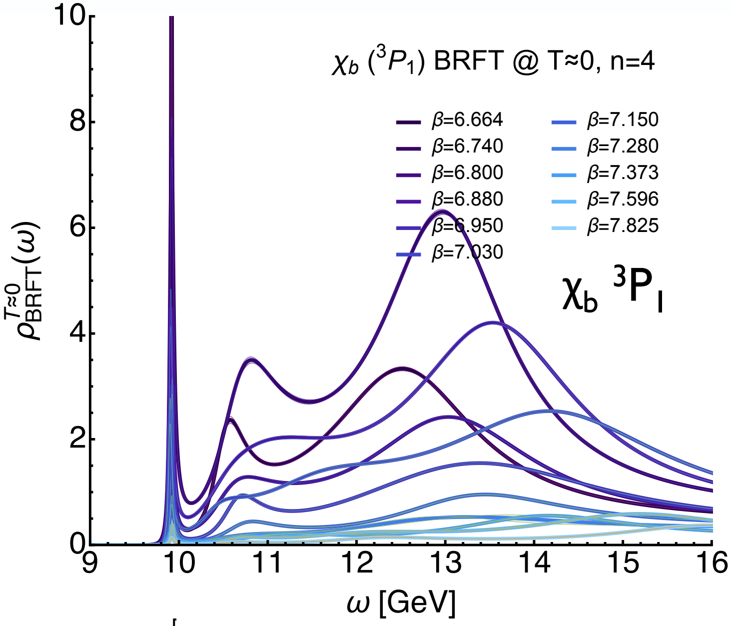
A.R. in preparation

Calibrating Bayesian spectra at T=0

S.Kim, P.Petreczky, A.R. in preparation



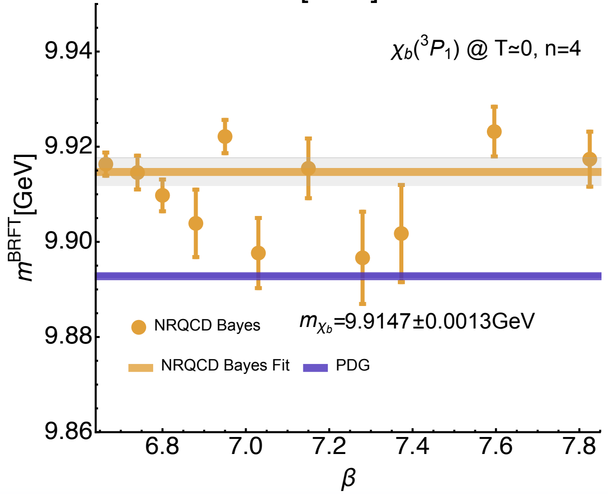
m_Υ from PDG to calibrate absolute freq. scale



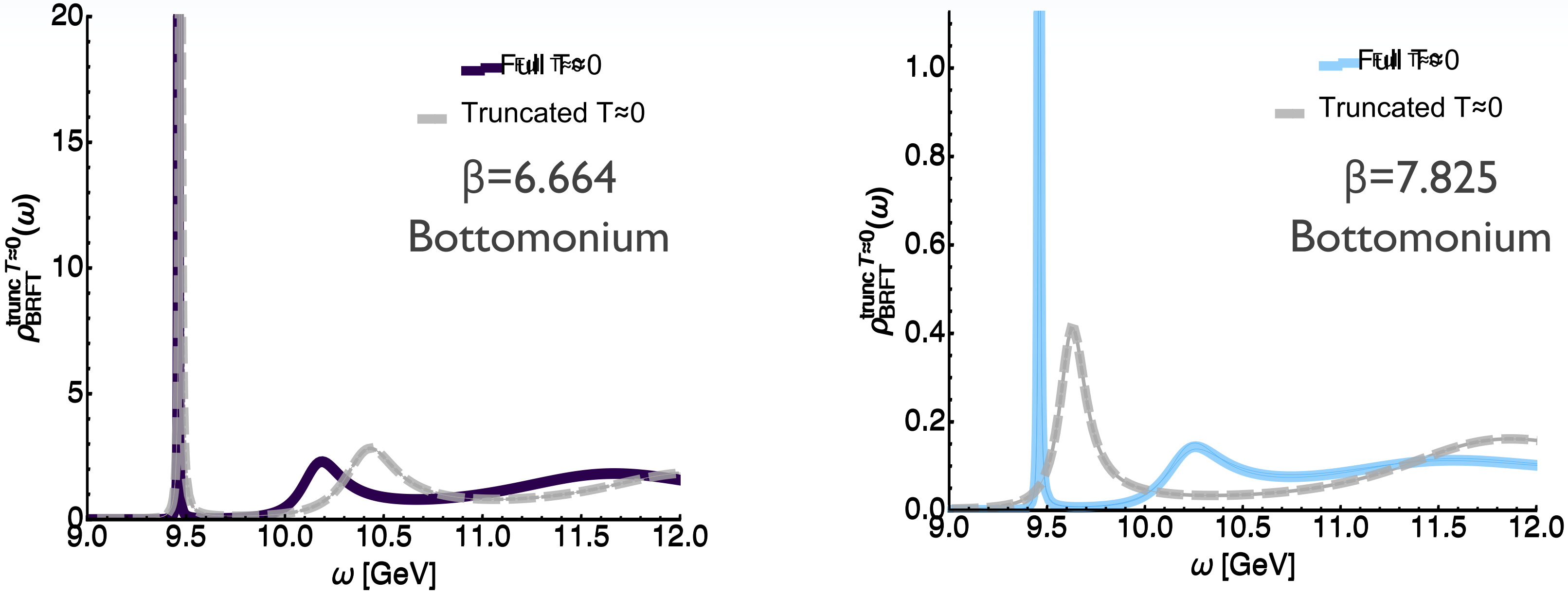
- Check systematic error of lattice computation by postdiction of P-wave ground state mass

$M^{\mathrm{NRQCD}}_{\chi b1}$=9.9147(13) GeV $M^{\mathrm{PDG}}_{\chi b1}$=9.89278(3) GeV

$M^{\mathrm{NRQCD}}_{\chi c1}$=3.5086(39) GeV $M^{\mathrm{PDG}}_{\chi c1}$=3.51066(7) GeV



Taking control of systematics I



S.Kim, P.Petreczky, A.R. in preparation

$\Delta M_{6.664}$=9.3(2)MeV

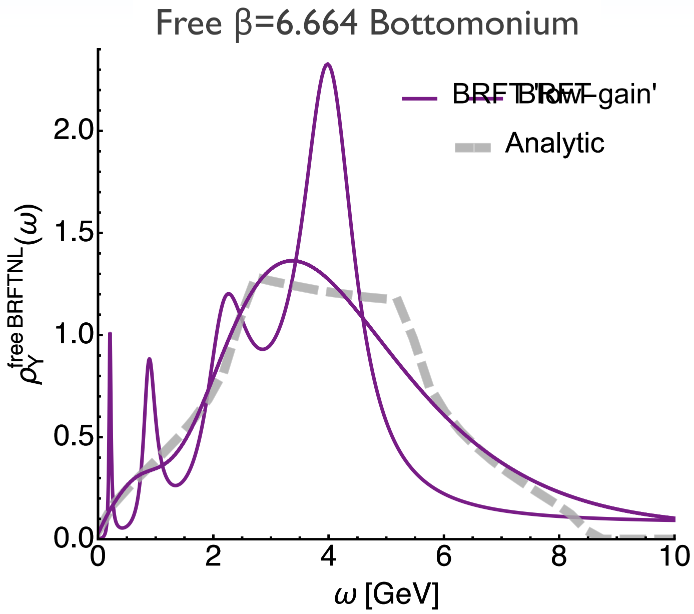
$\Delta M_{7.825}$=159(1)MeV

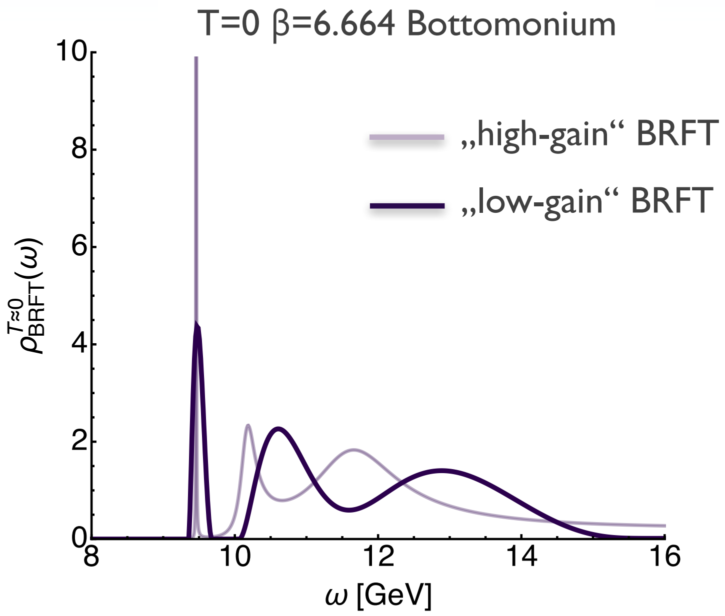
- The “high-gain” BR method resolves the T=0 ground state very well from N_τ=48-64 points
- How does accuracy suffer from limited available information at T>0 (N_τ=12) ?

→ Systematic shift of peaks to higher frequencies, as well as broadening.
needs to be accounted for when analyzing T>0 spectra

Taking control of systematics II

S.Kim, P.Petreczky, A.R. in preparation

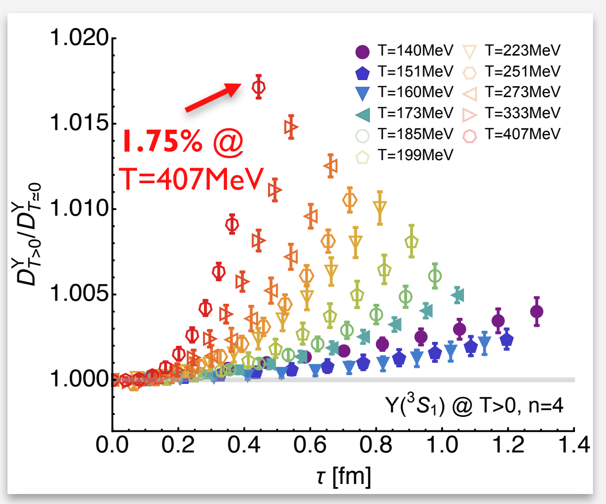

Free β=6.664 Bottomonium


T=0 β=6.664 Bottomonium

- Standard “high-gain” BR on small (N_τ=12) simulation datasets suffers from ringing
- New “low-gain” BR removes ringing from reconstructed analytic free spectra at low ω
- New ”low-gain” BR method still identifies presence of peaks encoded in data
- Strategy: - Test with “low-gain” reconstruction whether peaks are genuine
  - Use “high-gain” reconstruction to extract peak features, e.g. position

T>0 effects in $Q\bar{Q}$ correlators

E_{bind} (T=0)~1.1GeV

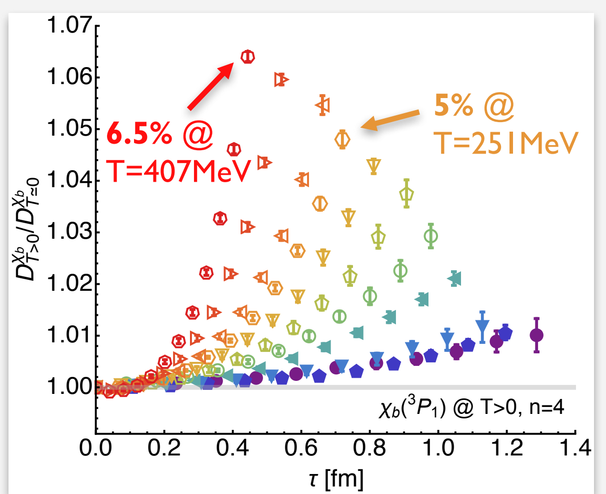


1.75% @ T=407MeV

S.Kim, P.Petreczky, A.R. in preparation

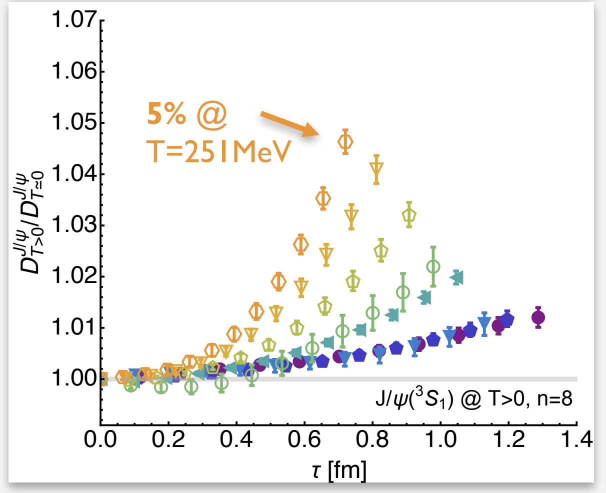
- Upsilon shows non-monotonous behavior around T~T_C (bb 3S1 channel contains most excited states)
- Hierarchical T>0 modification w.r.t. vacuum binding energy

E_{bind} (T=0)~640MeV



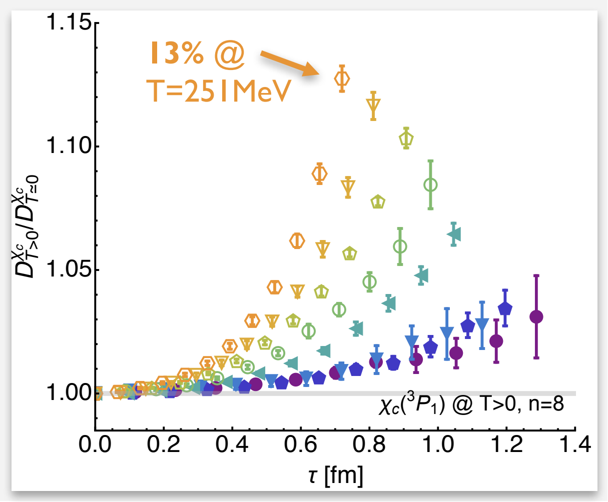
6.5% @ T=407MeV

5% @ T=251MeV



5% @ T=251MeV

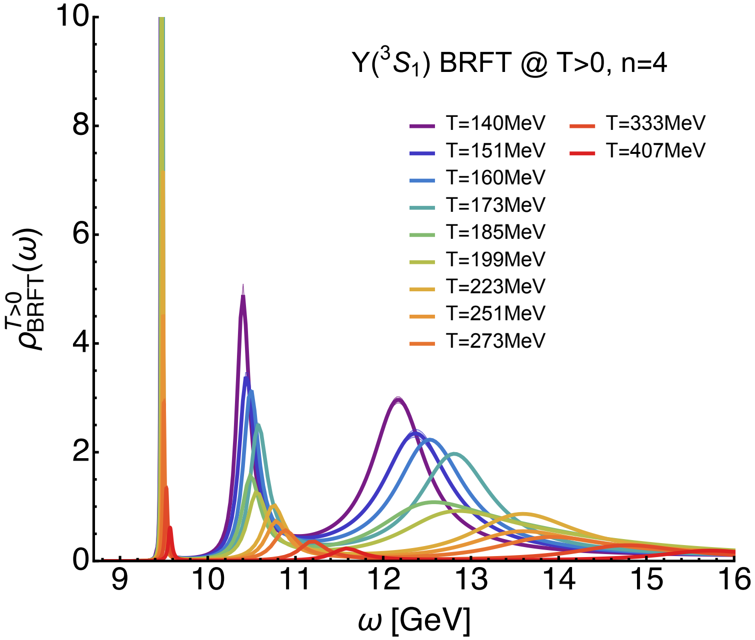
E_{bind} (T=0)~200MeV

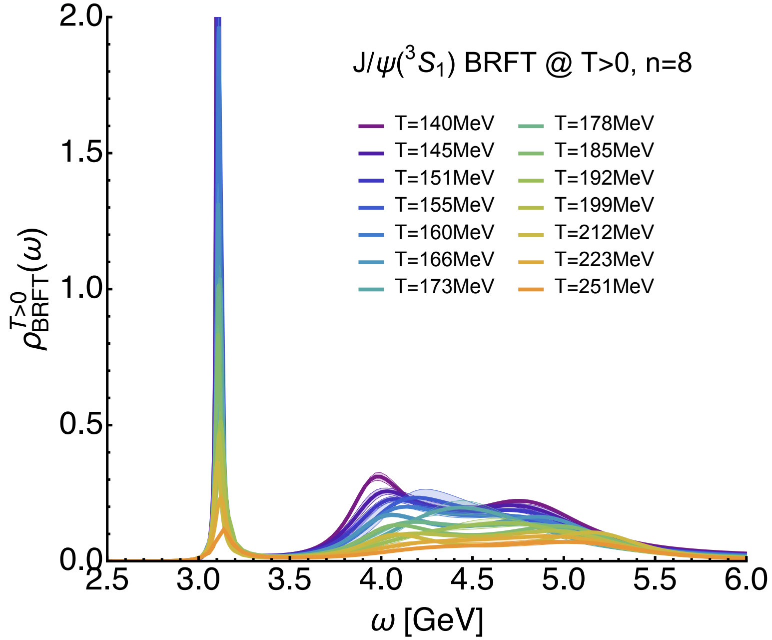


13% @ T=251MeV

NRQCD S-wave spectra at T>0

S.Kim, P.Petreczky, A.R. in preparation

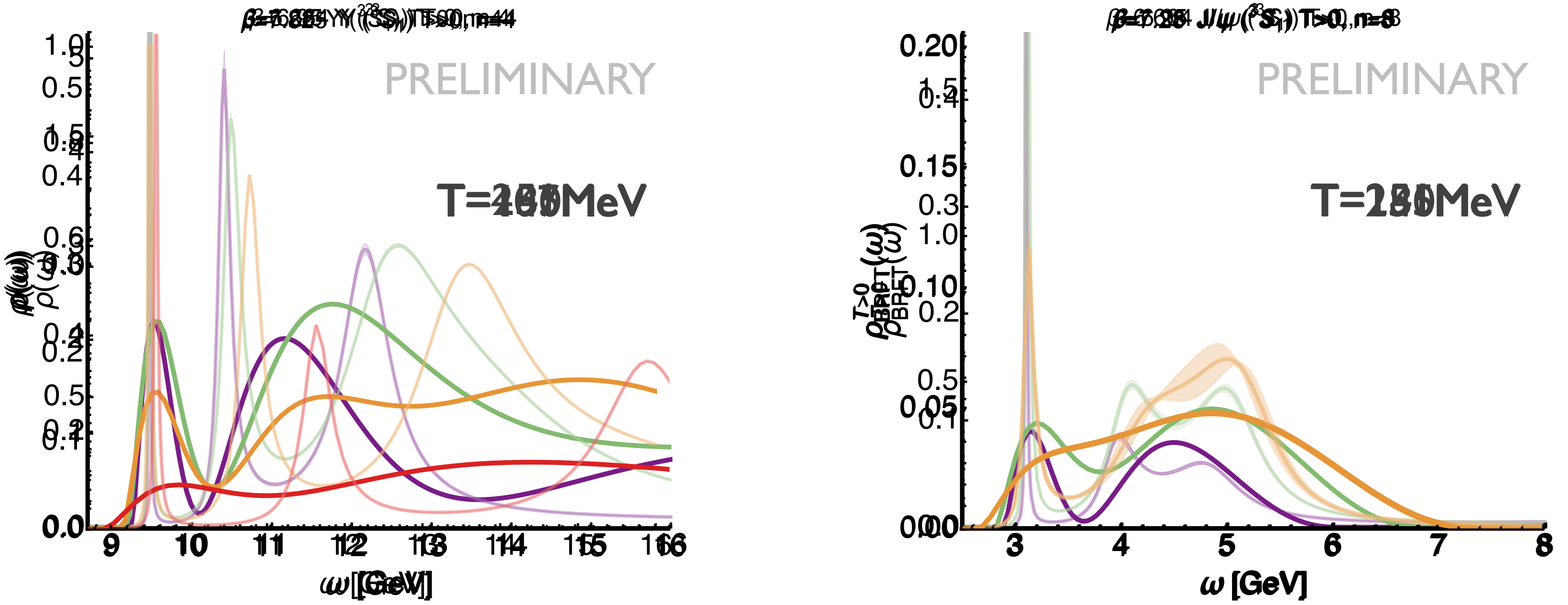




- Ground state well resolved and well separated from higher lying structures
- Combining Euclidean and imaginary frequency data reduces ringing at large ω
- Gradual broadening and shifting of lowest lying peak visible

Presence of ground state signals?

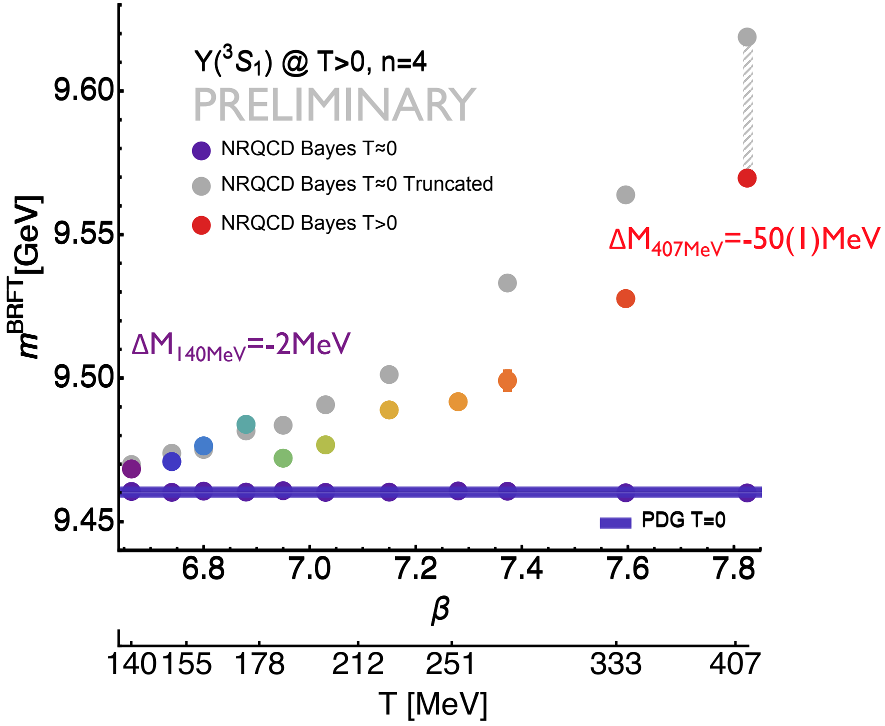
S.Kim, P.Petreczky, A.R. in preparation

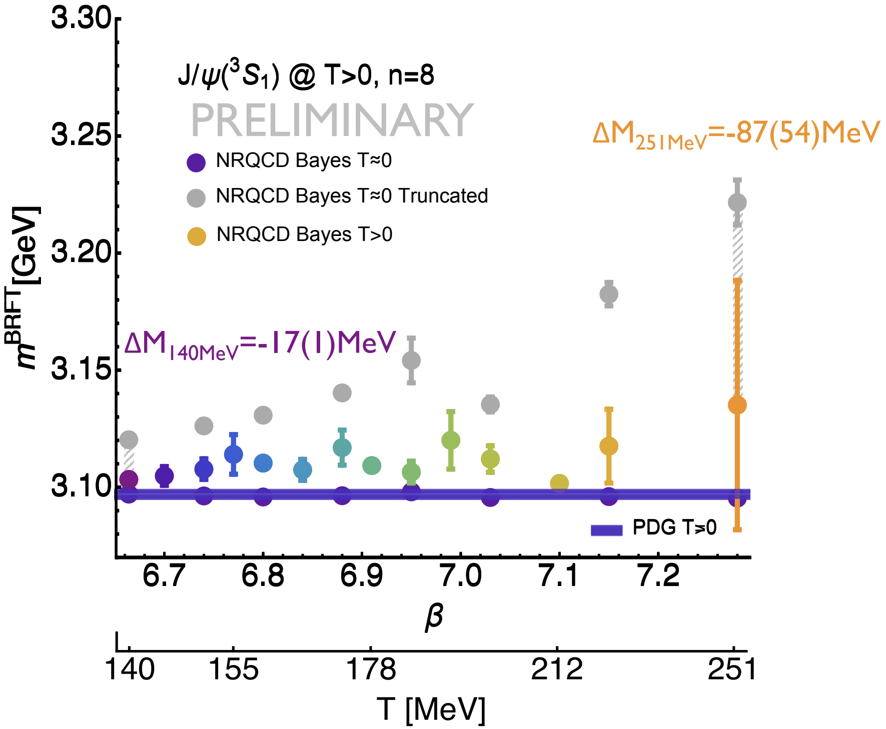


- New “low-gain” BR method shows gradual weakening of ground state signal
- At highest temperature in individual channels: weak ground state remnants remain visible

Upsilon signal up to T=407MeV   Faint J/ψ signal up to T=251MeV

In-medium S-wave mass shifts

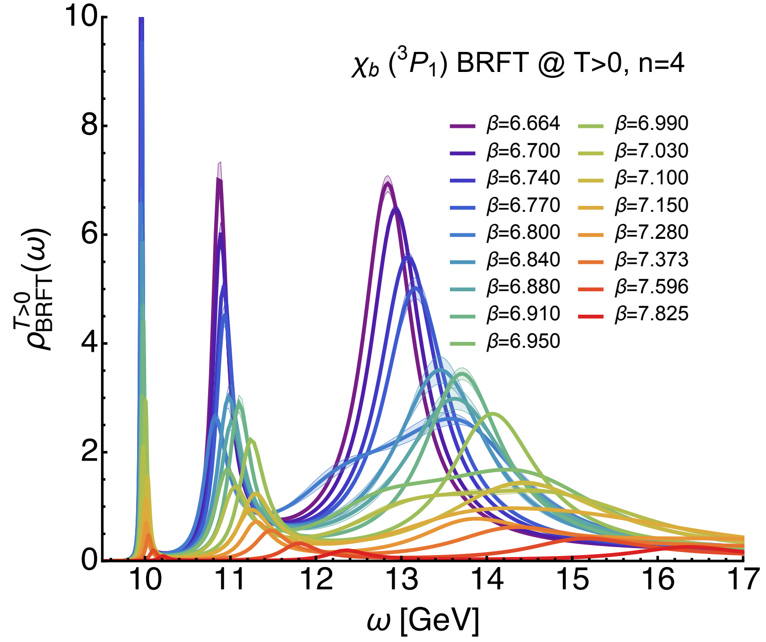


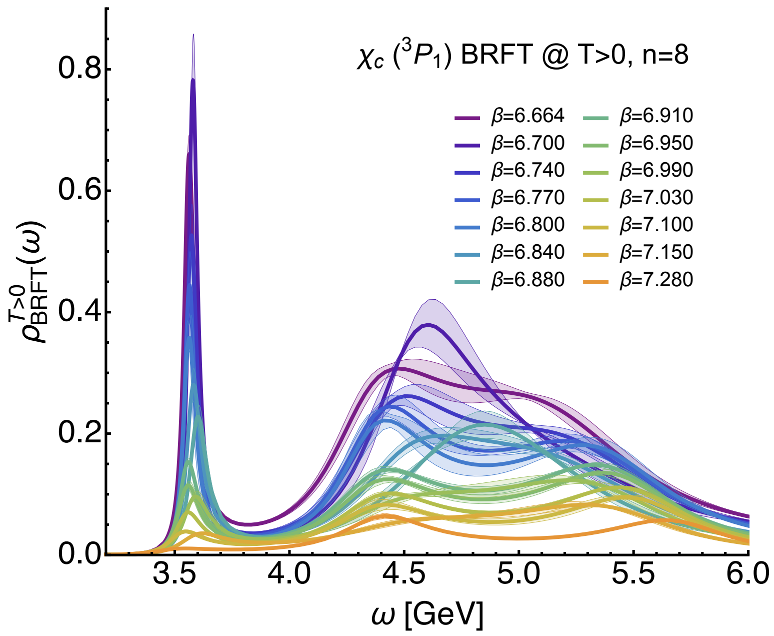


- Naïve inspection of in-medium modification appears to show increasing masses
- BR method systematics: Low number of datapoints introduces shifts to larger masses
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies

NRQCD P-wave spectra at T>0

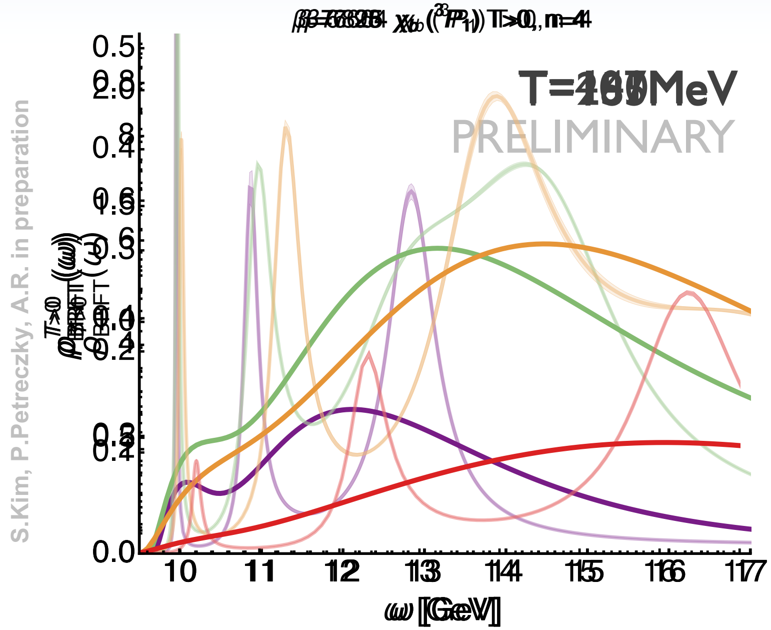
S.Kim, P.Petreczky, A.R. in preparation



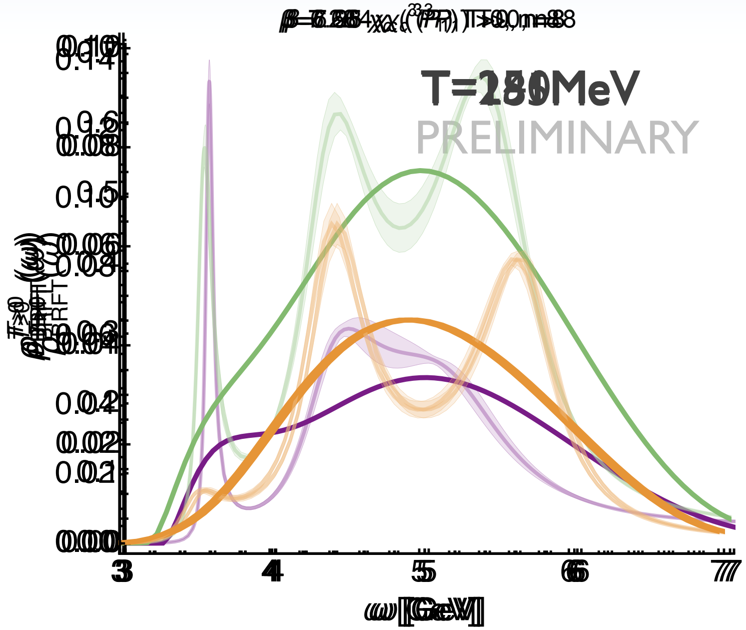


- Lower signal to noise ratio in underlying correlators makes reconstruction less precise
- Ground state well resolved and well separated from higher lying structures
- Gradual broadening and shifting of lowest lying peak visible

Survival of ground state signals?



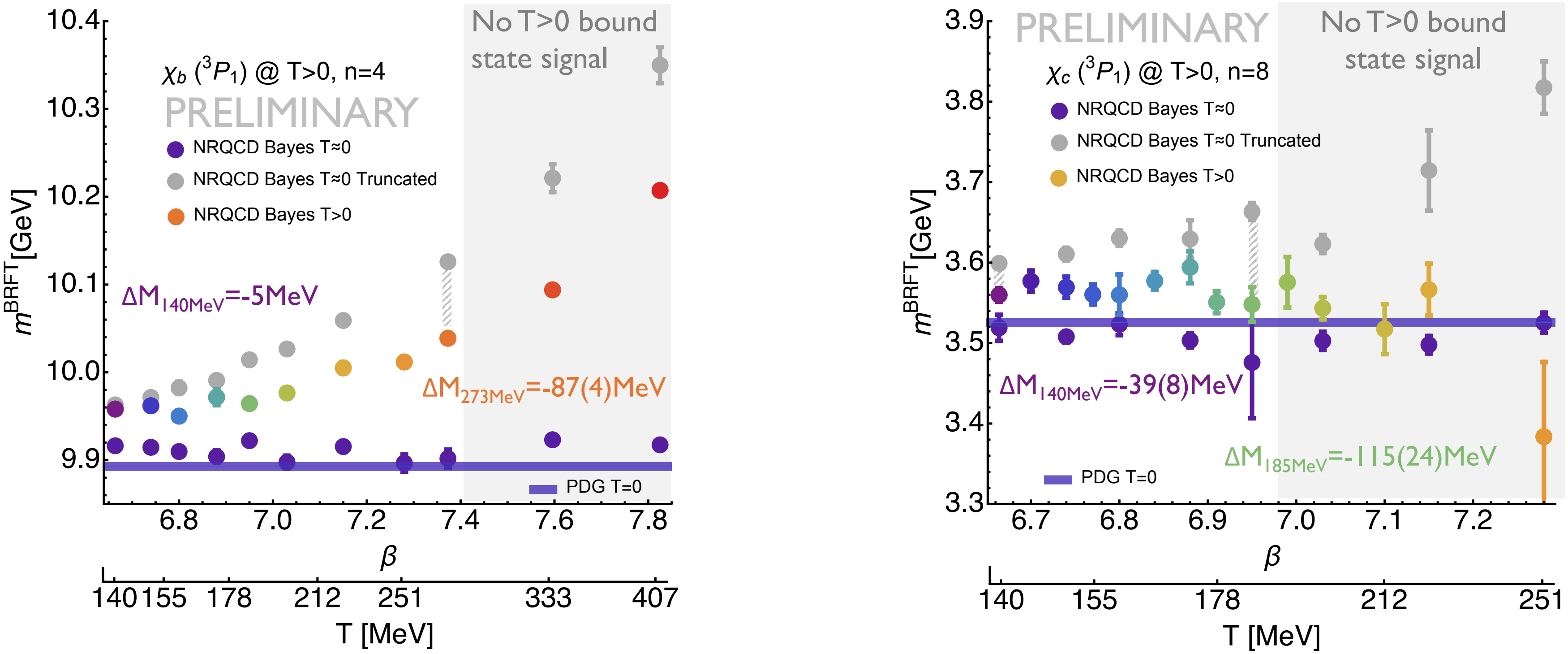
S.Kim, P.Petreczky, A.R. in preparation



- New “low-gain” BR method shows gradual weakening of ground state signal
- Genuine bound state signal lost at intermediate temperatures

χ_b signal up to T=273MeV χ_c signal up to T=185MeV

In-medium P-wave mass shifts



S.Kim, P.Petreczky, A.R. in preparation

- Naïve inspection of in-medium modification appears to show increasing masses
- BR method systematics: Low number of datapoints introduces shifts to larger masses
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies

Conclusions

- Heavy-ion experiments: Intricate quarkonium phenomenology

- Direct access to in-medium quarkonium from first principles: lattice NRQCD

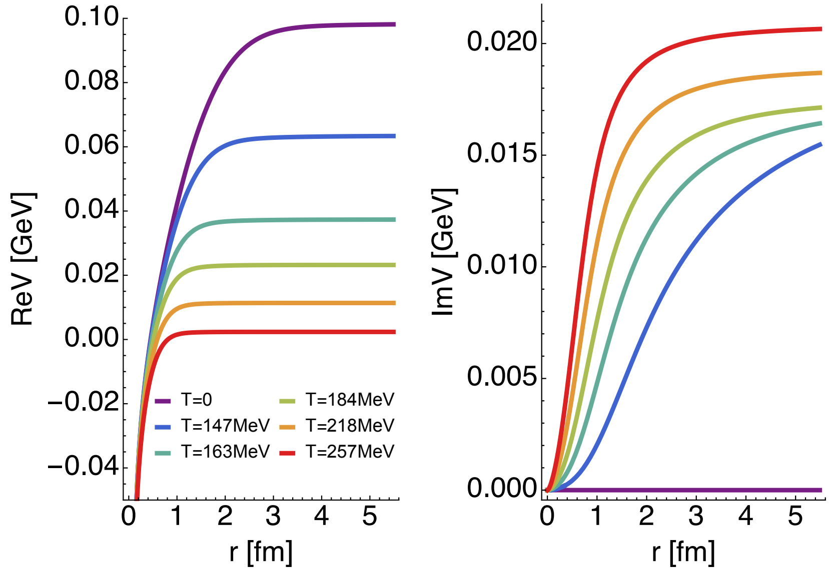
  S.Kim, P. Petreczky, A.R.: Phys.Rev. D91 (2015) 54511, Nucl.Phys. A956 (2016) 713 and arXiv:1704.05221

  - **Progress I:** HotQCD lattices provide higher statistics and larger temperature range
  - **Progress II:** Improved Bayesian spectral reconstruction reduces methods uncertainties
  - **Progress III:** Extension of our previous study to charmonium at finite temperature

- Updated in-medium results for quarkonium in lattice NRQCD:
  - Verified **sequential** in-medium **modification** of correlators according to vacuum E_{bind}
  - First quantitative determination of in-medium **shifts** to **lower masses**

Thank you for your attention - Благодарю вас за внимание

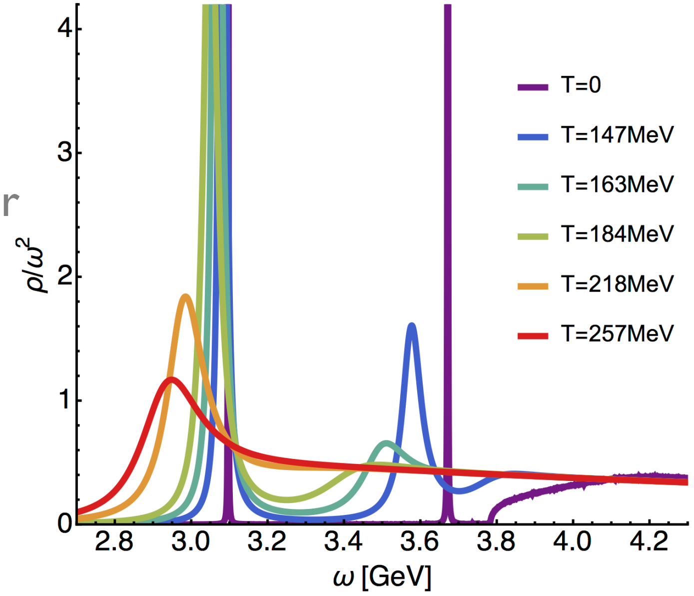
Previous lessons from the lattice $V_{Q\bar{Q}}$



From full QCD with u,d,s quarks based on asqtad action

Schrödinger equation

$^3S_1$ Charmonium channel

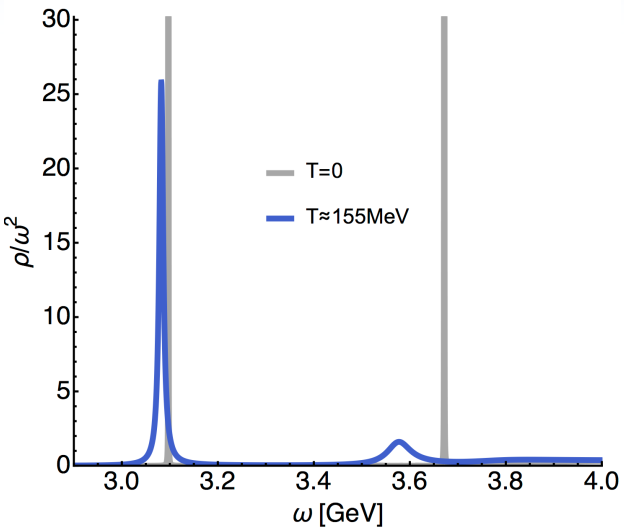


Y.Burnier, O.Kaczmarek, A.R.
JHEP 1512 (2015) 101

- $Q\bar{Q}$ states suffer from a hierarchical in-medium modification w.r.t. vacuum binding energy
- In-medium states take on *lower* masses and show *increased* thermal widths
- Quarkonium melting is a gradual process: defining T_{melt} is *ambiguous*, popular $E_{bind}=\Gamma_{therm}$
- Observables from in-medium spectra: ψ' / J/ψ ratio and P-wave feed-down estimated

Y.Burnier, O.Kaczmarek, A.R. JHEP 1512 (2015) 101, JHEP 1610 (2016) 032

ψ‘ to J/ψ ratio from T>0 spectra



Y.Burnier, O.Kaczmarek, A.R.
JHEP 1512 (2015) 101

- Assume instantaneous freezeout: T>0 states convert to real vacuum particles at around T_C
- In-medium dilepton emission from area under spectral resonance peaks

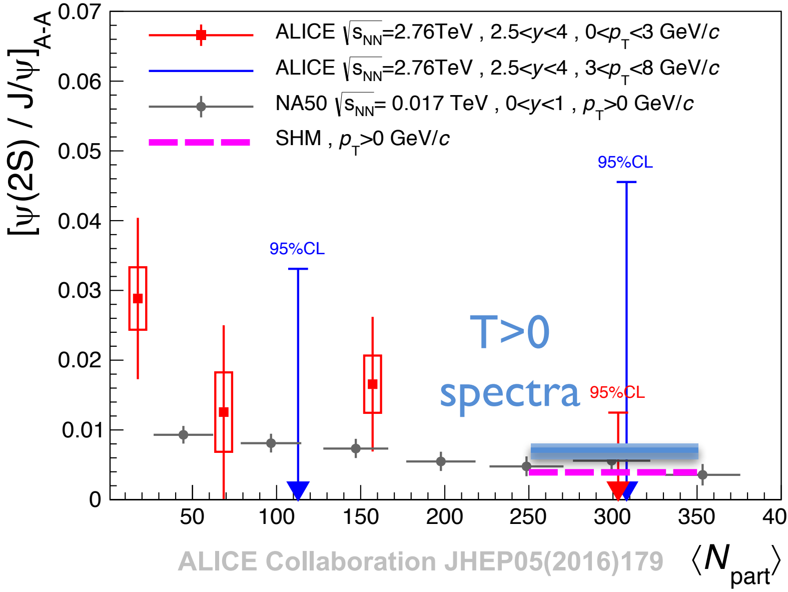
$$R_{\ell\bar{\ell}} \propto \int dp_0 \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{\rho(P)}{P^2} n_B(p_0)$$

(to leading order $\rho(P) = \rho(p_0^2 - \mathbf{p}^2)$)

- ”How many vacuum states do the in-medium peaks correspond to?”
- Number density: divide in-medium by T=0 dimuon emission rate:

$$\frac{N_{\Psi'}}{N_{J/\Psi}} = \frac{R^{\Psi'}_{\ell\bar{\ell}}}{R^{J/\Psi}_{\ell\bar{\ell}}} \frac{M^2_{\Psi'}|\Phi_{J/\Psi}(0)|^2}{M^2_{J/\Psi}|\Phi_{\Psi'}(0)|^2}$$

Y.Burnier, O. Kaczmarek, A.R.
JHEP 1512 (2015) 101



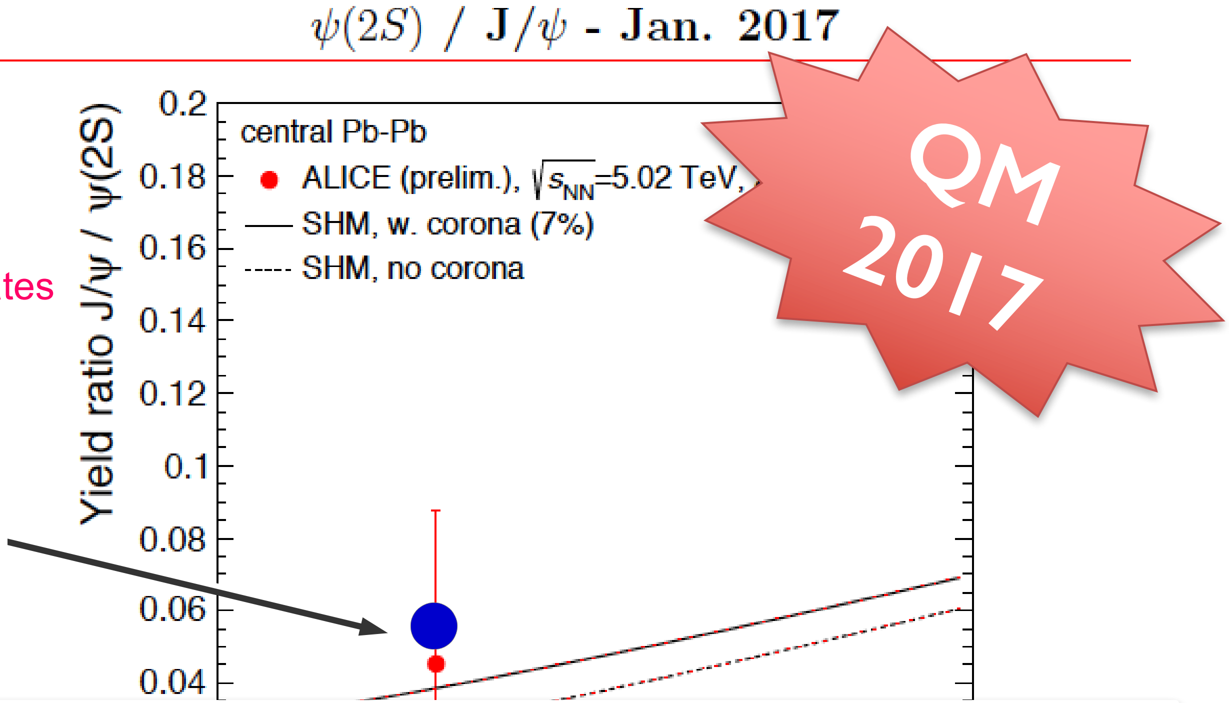
T>0 spectra

ALICE Collaboration JHEP05(2016)179

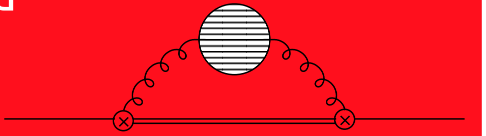
First preliminary ALICE data

settle question of
hadronic bound states
in the QGP

Our T>0
spectral
function
prediction



Not all in-medium effects on QQ can be captured
in a Schrödinger equation with potential:
crosscheck results with a *genuine* field theory



ALICE data, Pb–Pb: Quark Matter 2017; pp: arXiv:1702.00557

slide from
Peter Braun-Munzinger