Deutsche Forschungsgemeinschaft

ISOQUANT SFB1225

In-medium heavy quarkonium from lattice effective field theories

Alexander Rothkopf
Institute for Theoretical Physics
Heidelberg University

References:

with Y. Burnier and O.Kaczmarek	JHEP 1512 (2015) 101
	JHEP 1610 (2016) 032
with S.Kim and P. Petreczky	PRD91 (2015) 054511, NPA956 (2016) 713
	in preparation
with J. Pawlowski	arXiv:1610.09531

Motivation: Heavy-Ion Collisions

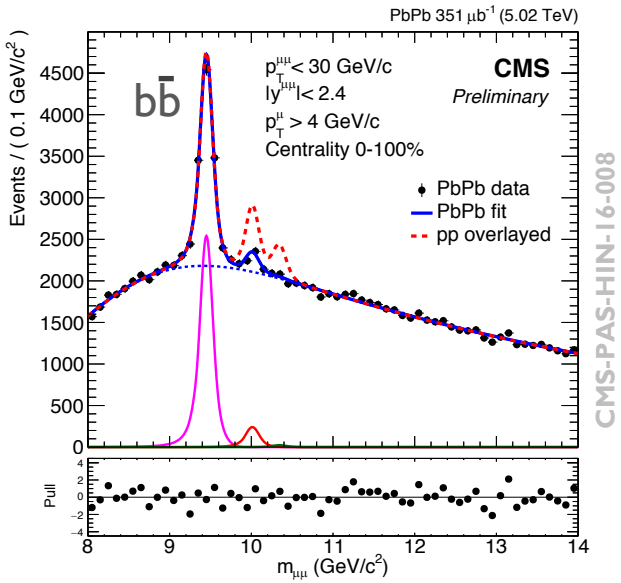
- Our interest: probes susceptible to medium but distinguishable $Q_{probe} >> T_{med}$

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

Motivation: Heavy-Ion Collisions

- Our interest: probes susceptible to medium but distinguishable $Q_{probe} >> T_{med}$

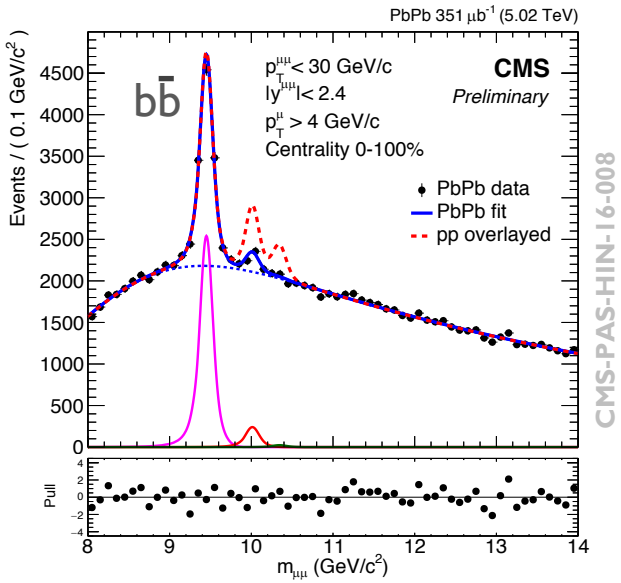
Bound states of $c\bar{c}$ or $b\bar{b}$: **Heavy quarkonium** $M_Q >> T_{med}$

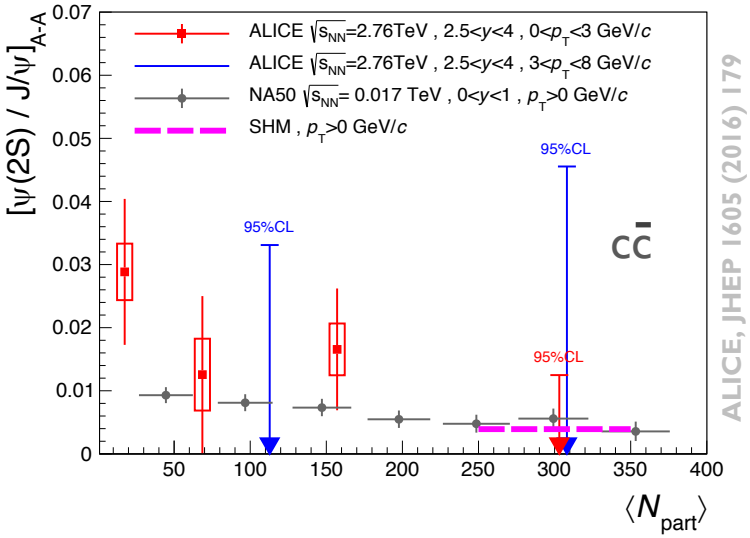


Motivation: Heavy-Ion Collisions

- Our interest: probes susceptible to medium but distinguishable $Q_{probe} >> T_{med}$

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

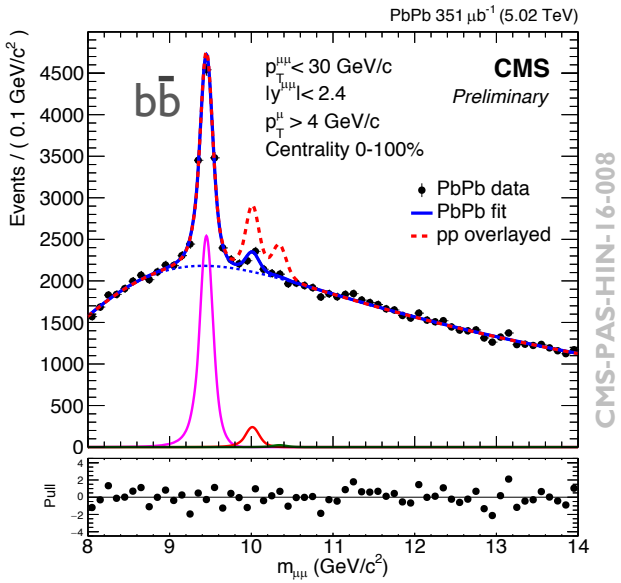


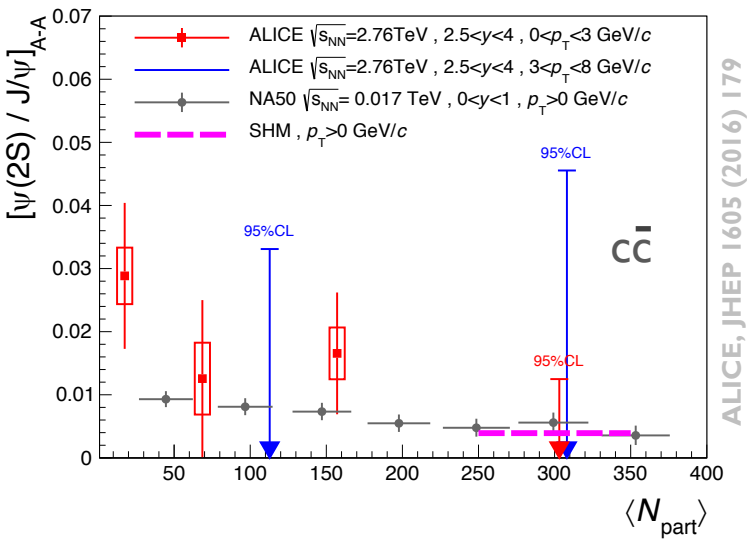


Motivation: Heavy-Ion Collisions

- Our interest: probes susceptible to medium but distinguishable $Q_{probe} >> T_{med}$

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



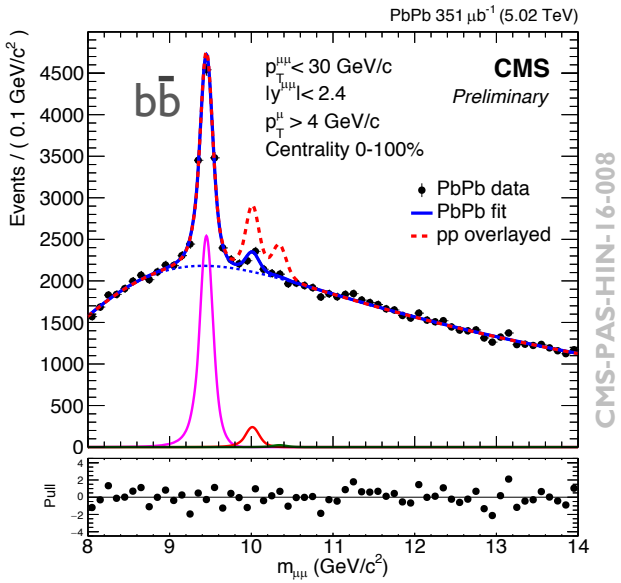


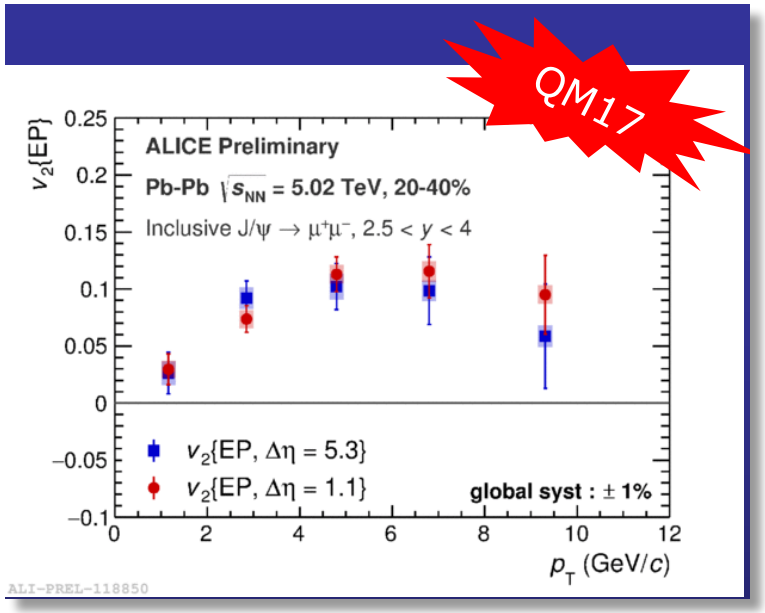
- Goal: in-medium properties of a fully thermal heavy quarkonium system

Motivation: Heavy-Ion Collisions

- Our interest: probes susceptible to medium but distinguishable $Q_{probe} >> T_{med}$

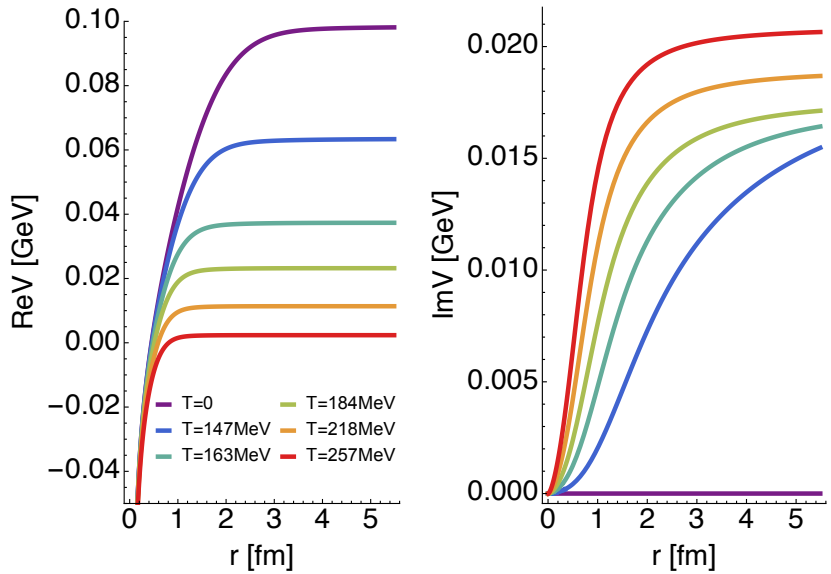
Bound states of $c\bar{c}$ or $b\bar{b}$: **Heavy quarkonium** $M_Q >> T_{med}$





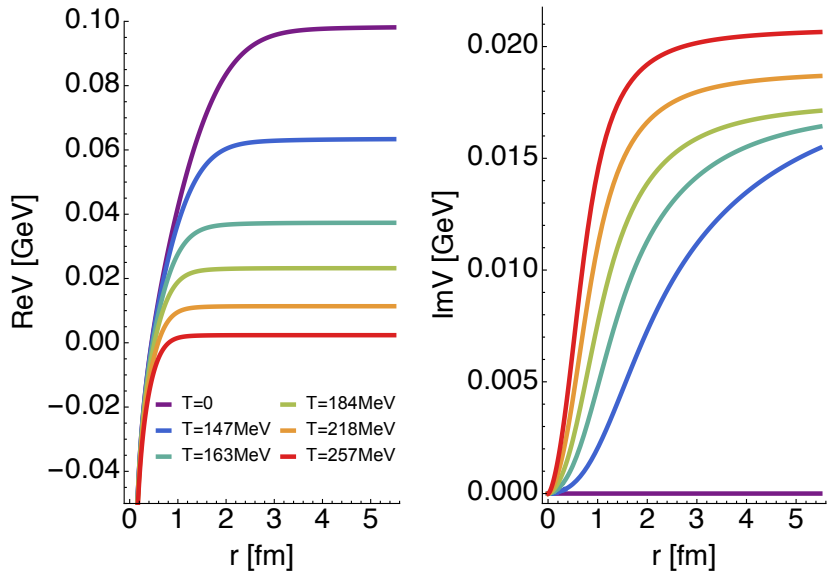
- Goal: in-medium properties of a fully thermal heavy quarkonium system

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



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

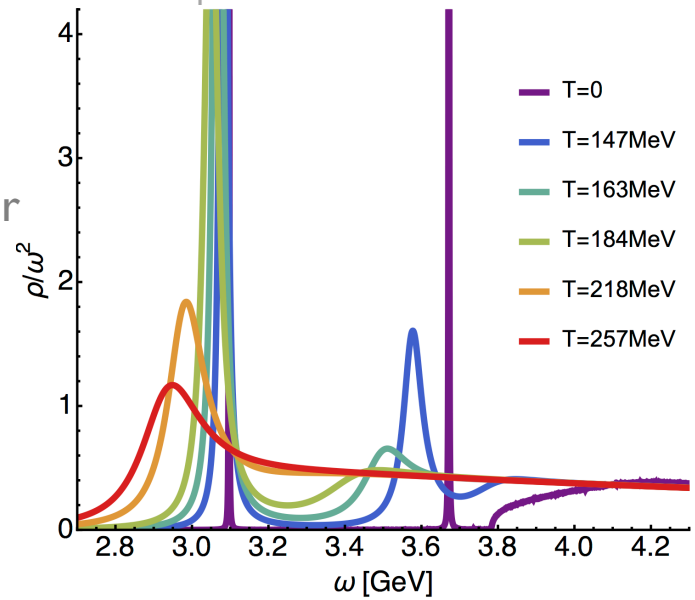
Previous lessons from the lattice $V_{Q\bar{Q}}$



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

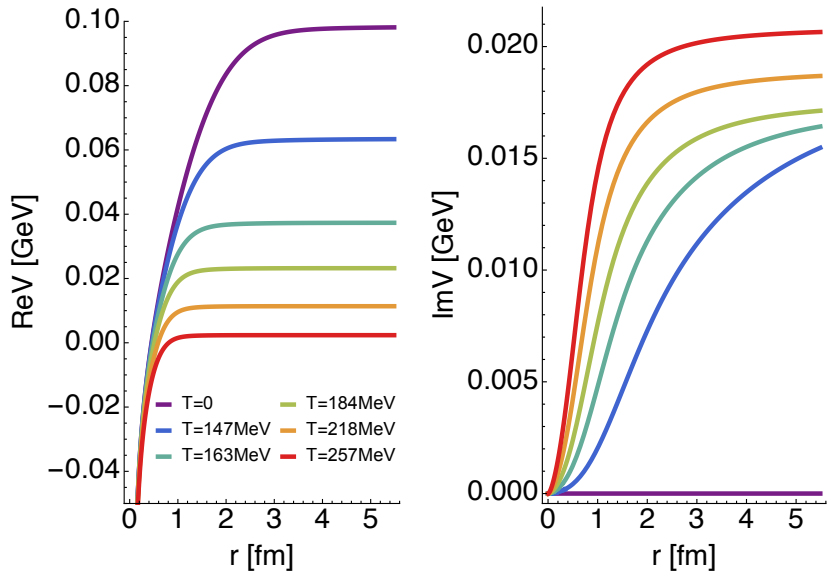
Schrödinger equation

$^3S_1$ Charmonium channel



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

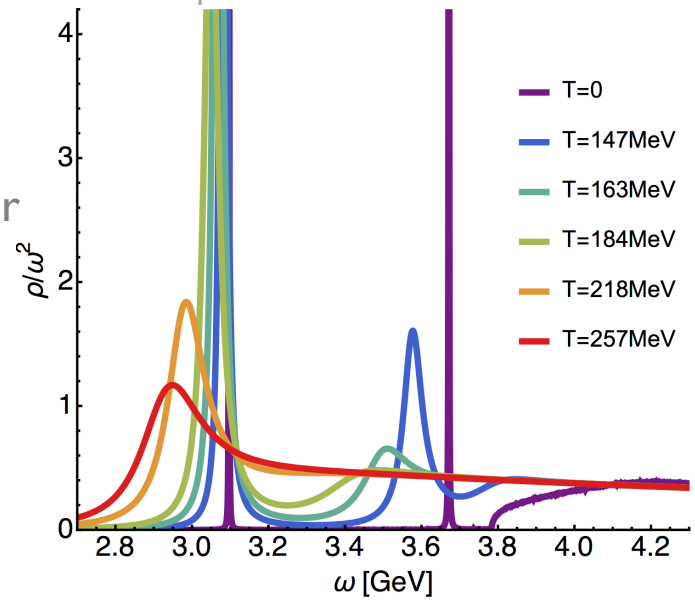
Previous lessons from the lattice $V_{Q\bar{Q}}$



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

Schrödinger equation

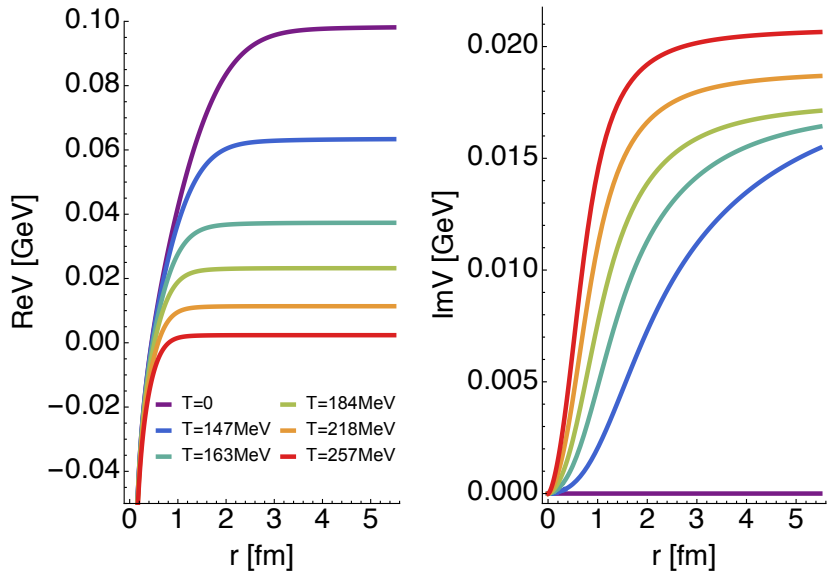
$^3S_1$ Charmonium channel



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

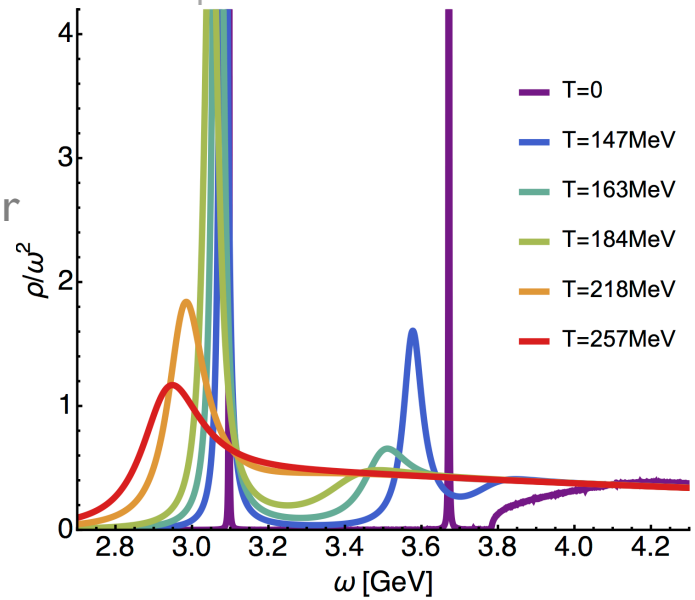
Previous lessons from the lattice $V_{Q\bar{Q}}$



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

Schrödinger equation

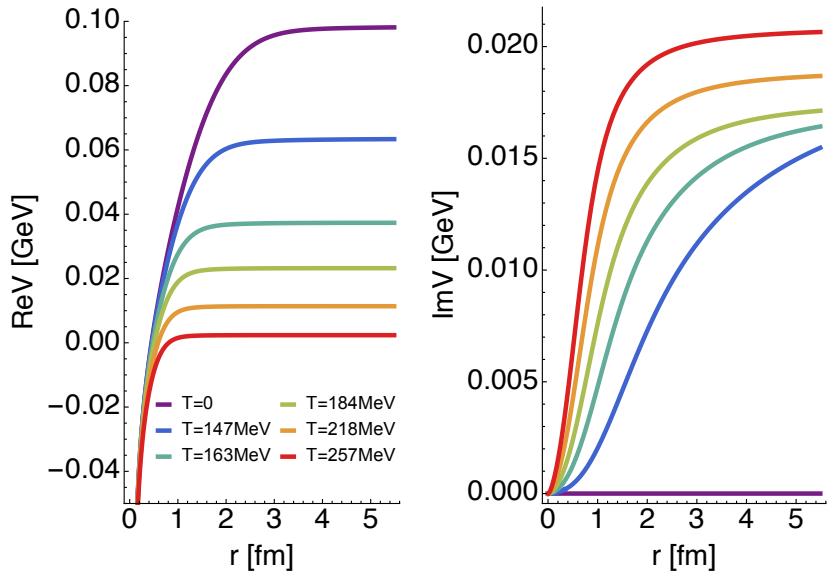
$^3S_1$ Charmonium channel



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

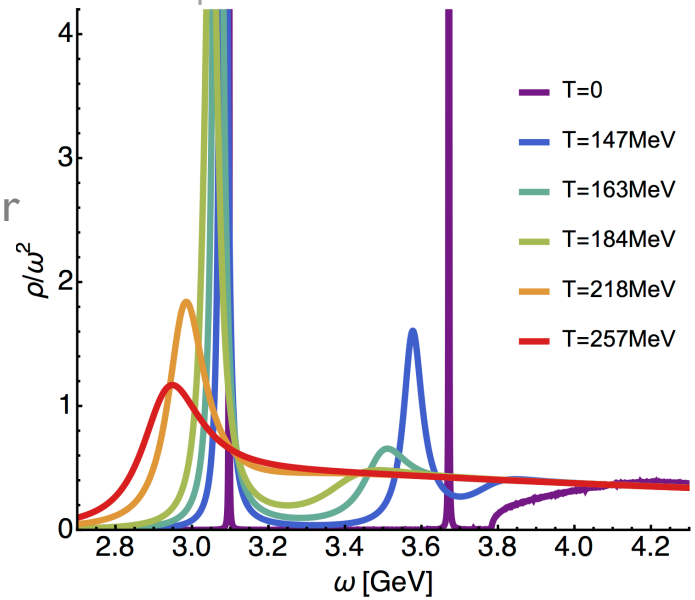
Previous lessons from the lattice $V_{Q\bar{Q}}$



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

Schrödinger equation

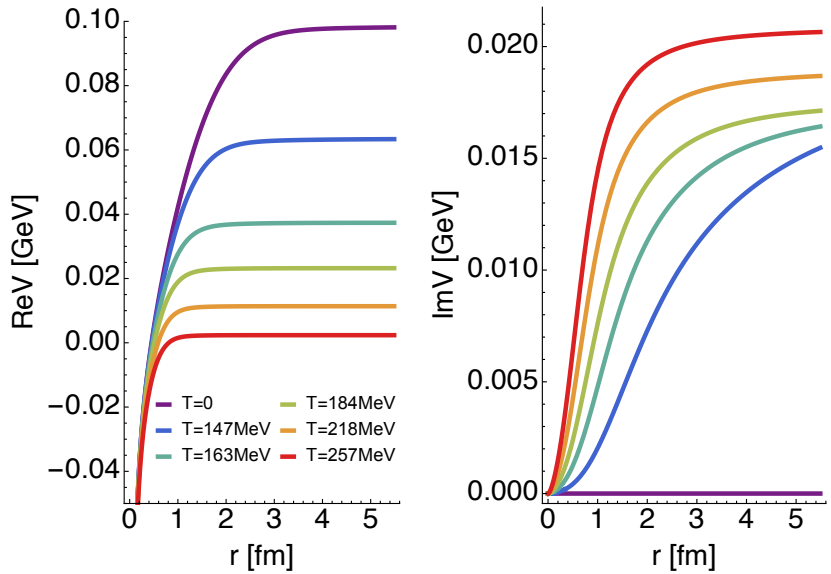
$^3S_1$ Charmonium channel



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 $E_{bind}=\Gamma_{therm}$

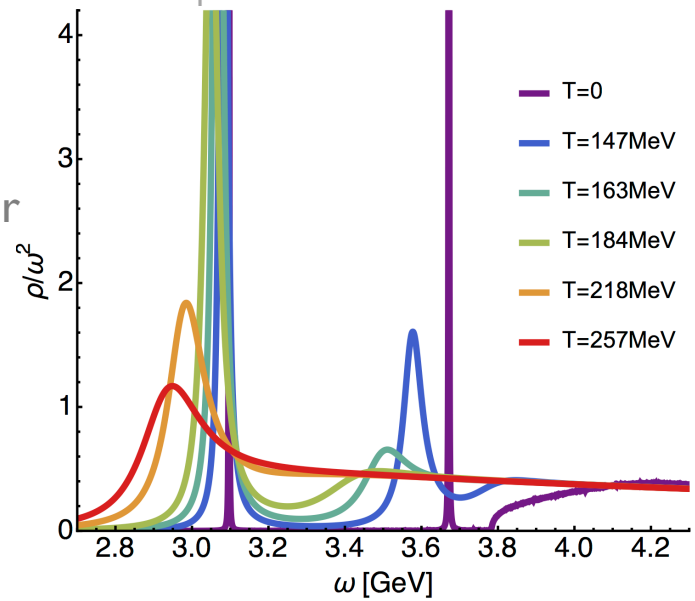
Previous lessons from the lattice $V_{Q\bar{Q}}$



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

Schrödinger equation

$^3S_1$ Charmonium channel



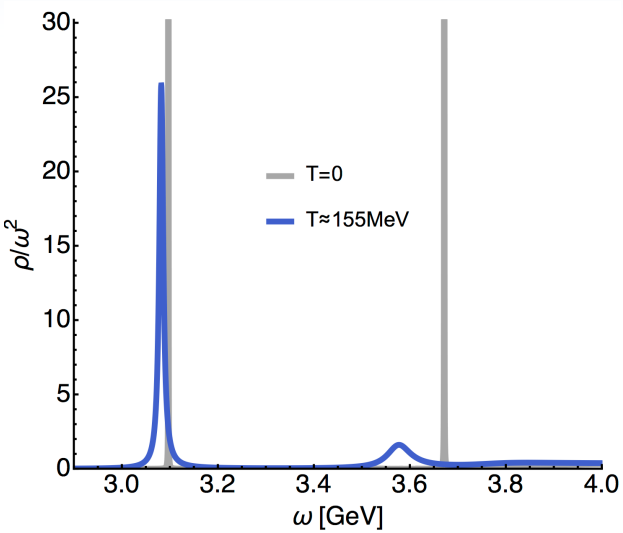
Y.Burnier, O.Kaczmarek, A.R. JHEP 1512 (2015) 101

- $Q\bar{Q}$ 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

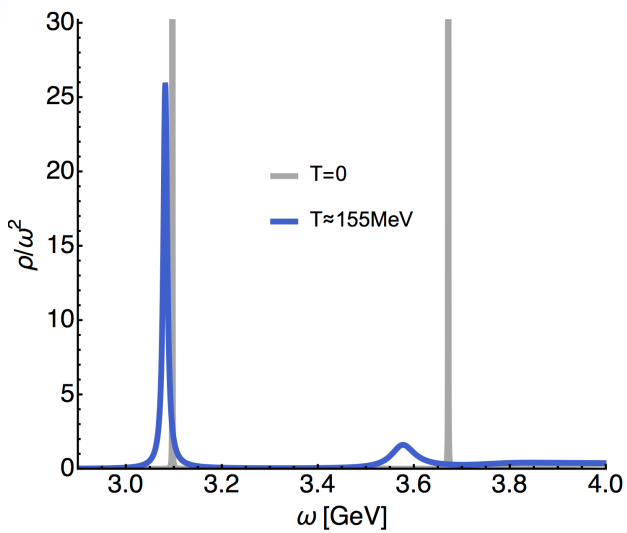
Y.Burnier, O.Kaczmarek, A.R.
JHEP 1512 (2015) 101



- Assume instantaneous freezeout: T>0 states convert to real vacuum particles at around T_C

ψ‘ to J/ψ ratio from T>0 spectra

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



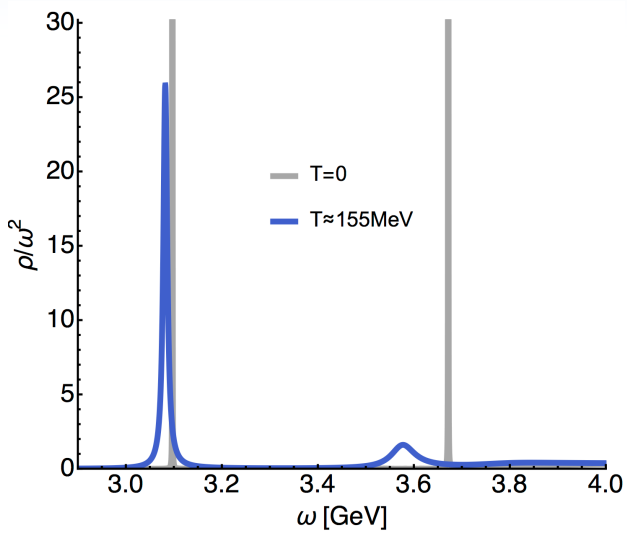
- Assume instantaneous freezeout: T>0 states convert to real vacuum particles at around T_C
- In-medium dilepton emission from area under spectral resonance peaks

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

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

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

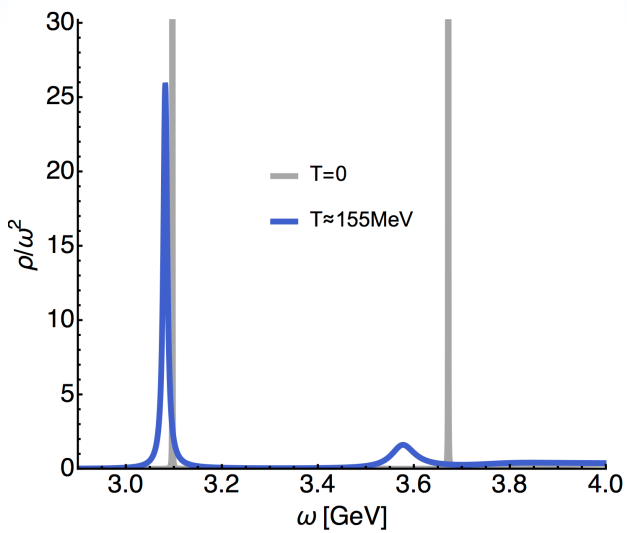
$$R_{\ell\bar{\ell}} \propto \int dp_0 \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{\rho(P)}{P^2} n_B(p_0)$$

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

- ”How many vacuum states do the in-medium peaks correspond to?”

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

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

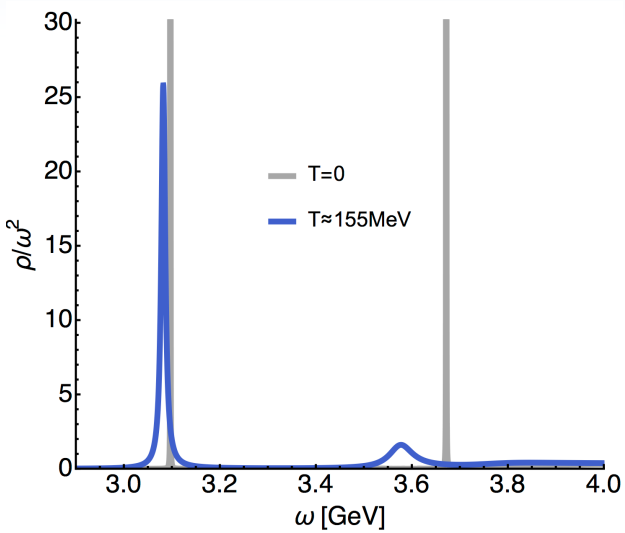
(to leading order $\rho(P) = \rho(p_0^2 - \mathbf{p}^2)$)

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

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

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

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

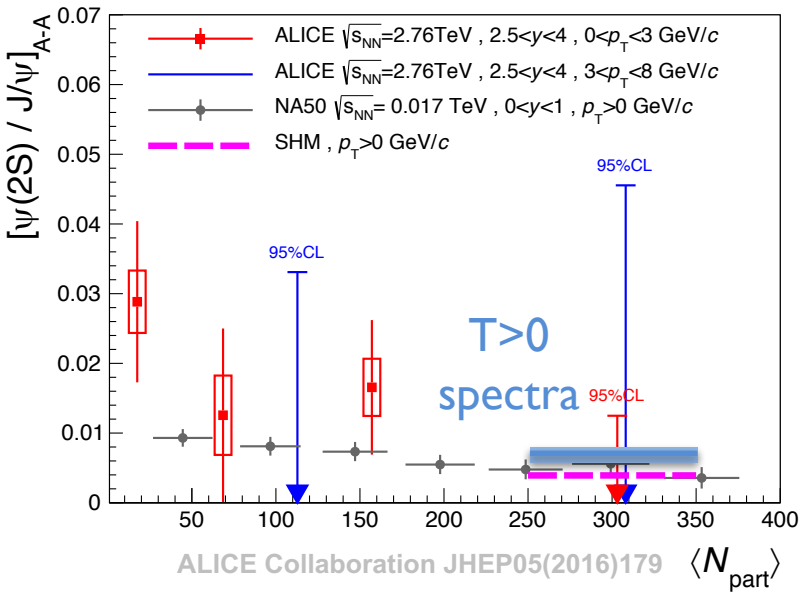
$$R_{\ell\bar{\ell}} \propto \int dp_0 \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{\rho(P)}{P^2} n_B(p_0)$$

(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:

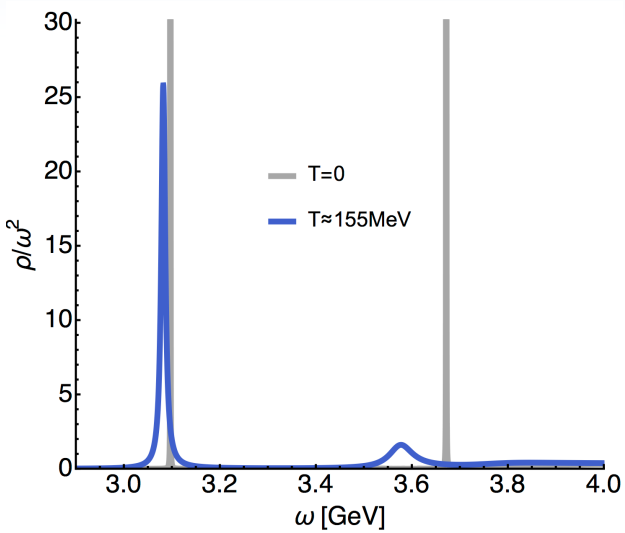
$$\frac{N_{\Psi'}}{N_{J/\Psi}} = \frac{R^{\Psi'}_{\ell\bar{\ell}}}{R^{J/\Psi}_{\ell\bar{\ell}}} \frac{M^2_{\Psi'}|\Phi_{J/\Psi}(0)|^2}{M^2_{J/\Psi}|\Phi_{\Psi'}(0)|^2}$$

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



ALICE Collaboration JHEP05(2016)179

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

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

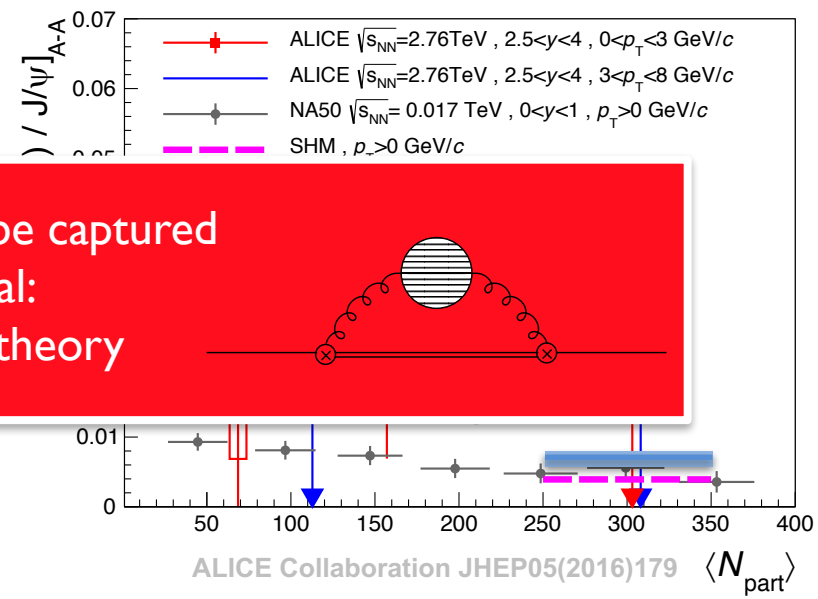
(to leading order $\rho(P) = \rho(p_0^2 - \mathbf{p}^2)$)

- ”How many vacuum states do the in-medium peaks correspond to?”
- [illegible]

Not all in-medium effects on $Q\bar{Q}$ can be captured in a Schrödinger equation with potential: crosscheck results with a *genuine* field theory

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

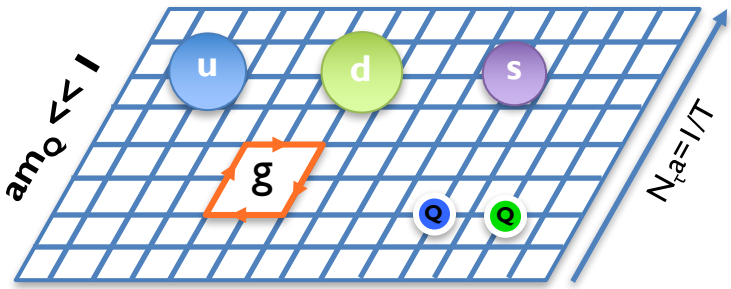
Y.Burnier, O. Kaczmarek, A.R. JHEP 1512 (2015) 101



ALICE Collaboration JHEP05(2016)179

Heavy quarks on the lattice

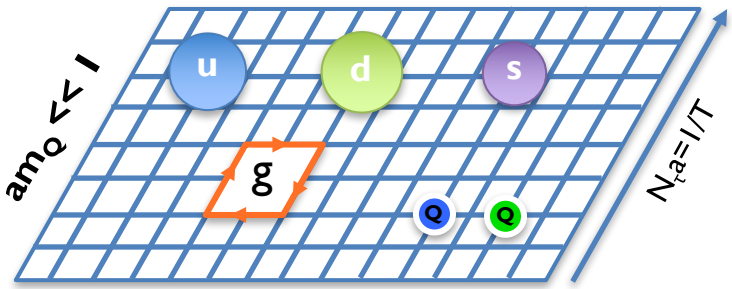
Relativistic treatment of light and heavy d.o.f.



Full Lattice QCD simulation incl. $Q\bar{Q}$
(still too costly)

Heavy quarks on the lattice

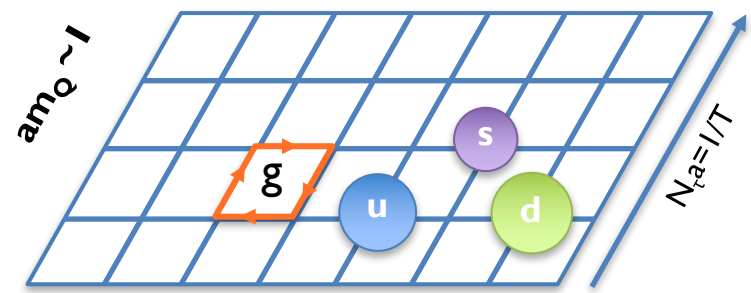
Relativistic treatment of light and heavy d.o.f.



Full Lattice QCD simulation incl. $Q\bar{Q}$
(still too costly)

$$\frac{\Lambda_{QCD}}{m_Q} \ll 1$$

$$\frac{T}{m_Q} \ll 1$$

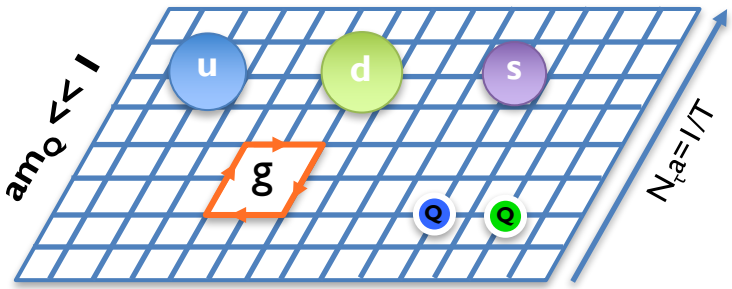


Lattice QCD simulation without $Q\bar{Q}$

Heavy quarks on the lattice

Relativistic treatment of light and heavy d.o.f.

Kin. eq. non-relativistic $Q\bar{Q}$ in a background of light medium d.o.f.

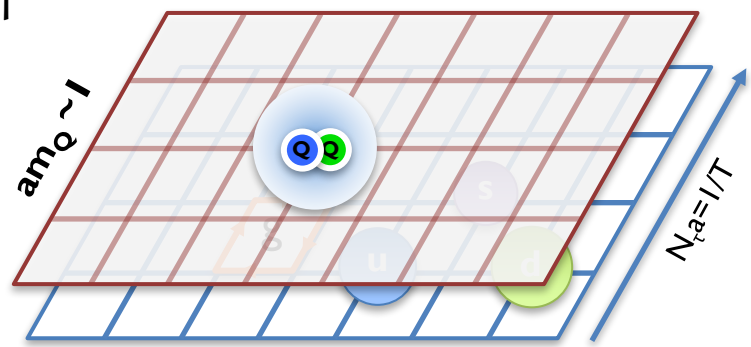


Full Lattice QCD simulation incl. $Q\bar{Q}$
(still too costly)

$$\frac{\Lambda_{QCD}}{m_Q} \ll 1$$

$$\frac{T}{m_Q} \ll 1$$

$Q\bar{Q}$ in NRQCD effective theory

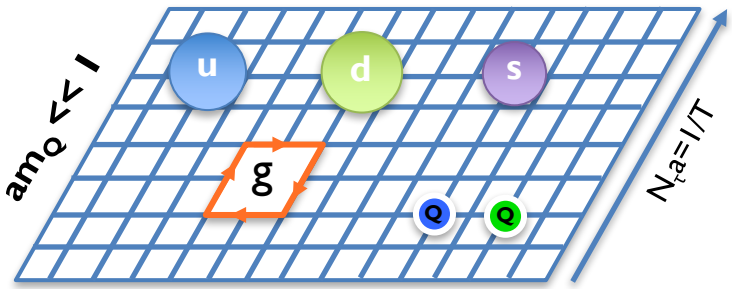


Lattice QCD simulation without $Q\bar{Q}$

Heavy quarks on the lattice

Relativistic treatment of light and heavy d.o.f.

Kin. eq. non-relativistic $Q\bar{Q}$ in a background of light medium d.o.f.

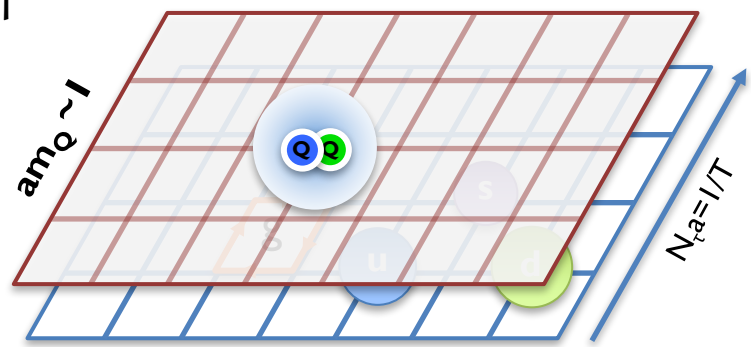


Full Lattice QCD simulation incl. $Q\bar{Q}$
(still too costly)

$$\frac{\Lambda_{QCD}}{m_Q} \ll 1$$

$$\frac{T}{m_Q} \ll 1$$

$Q\bar{Q}$ in NRQCD effective theory



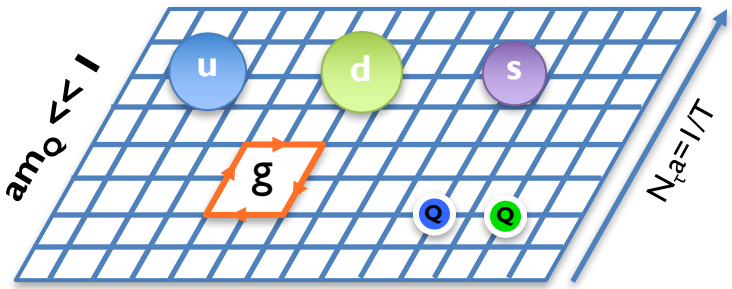
Lattice QCD simulation without $Q\bar{Q}$

- Lattice Non-Relativistic QCD (NRQCD) well **established** at T=0, applicable at T>0
  - no modeling, systematic expansion of QCD action in $1/M_Q a n$, includes $v \neq 0$ contributions
    Thacker, Lepage Phys.Rev. D43 (1991) 196-208
  - adaptive discretization in temporal direction: Lepage parameter n ($b\bar{b}$ n=4, $c\bar{c}$ n=8)

Heavy quarks on the lattice

Relativistic treatment of light and heavy d.o.f.

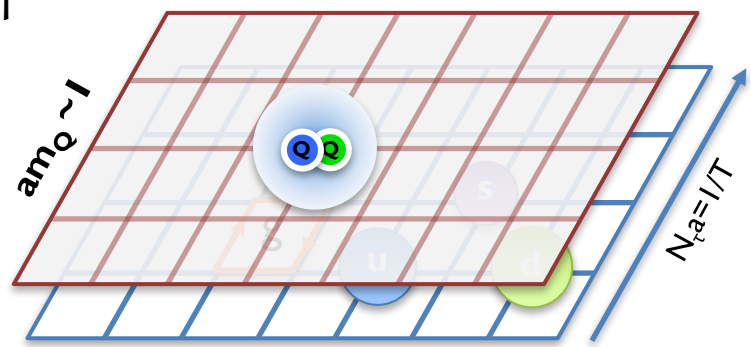
Kin. eq. non-relativistic $Q\bar{Q}$ in a background of light medium d.o.f.



Full Lattice QCD simulation incl. $Q\bar{Q}$
(still too costly)

$$\frac{\Lambda_{QCD}}{m_Q} \ll 1$$

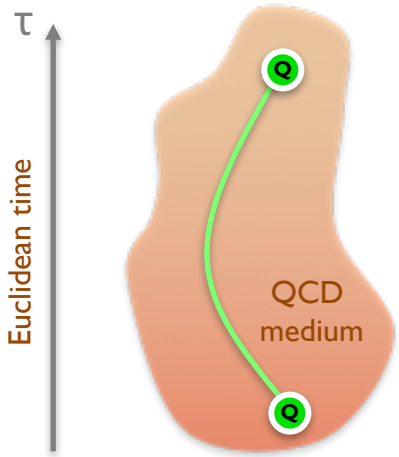
$$\frac{T}{m_Q} \ll 1$$



Lattice QCD simulation without $Q\bar{Q}$

- Lattice Non-Relativistic QCD (NRQCD) well **established** at T=0, applicable at T>0
  - no modeling, systematic expansion of QCD action in $1/M_Q a n$, includes $v \neq 0$ contributions
    Thacker, Lepage Phys.Rev. D43 (1991) 196-208
  - adaptive discretization in temporal direction: Lepage parameter n ($b\bar{b}$ n=4, $c\bar{c}$ n=8)
- Realistic simulations of the QCD medium by HotQCD collab. with extended T range
  HotQCD PRD85 (2012) 054503, PRD90 (2014) 094503
  - $48^3 \times 12$ m_π=161MeV (β=6.664-7.825) $M_b a$= [2.759 – 0.954] T= [140 – 407] MeV $M_c a$= [0.757 – 0.42] T= [140 – 251] MeV

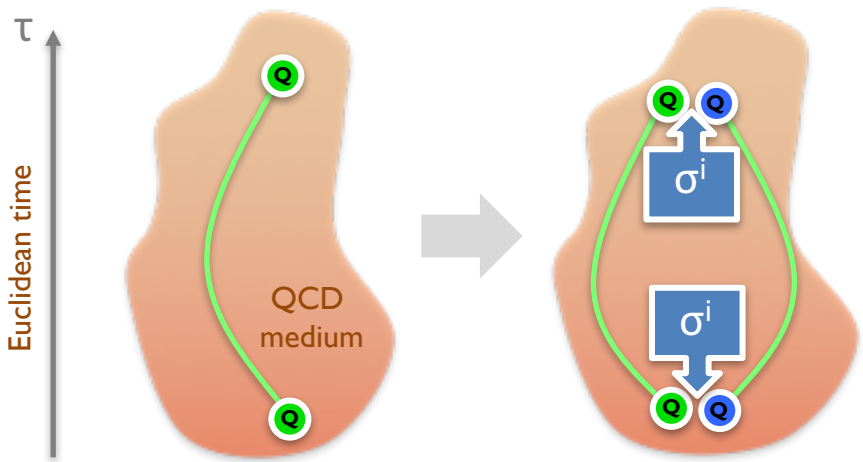
Correlation functions in NRQCD



Non-rel. propagator of
a single heavy quark G

Davies, Thacker Phys.Rev. D45 (1992)

Correlation functions in NRQCD



Non-rel. propagator of
a single heavy quark G

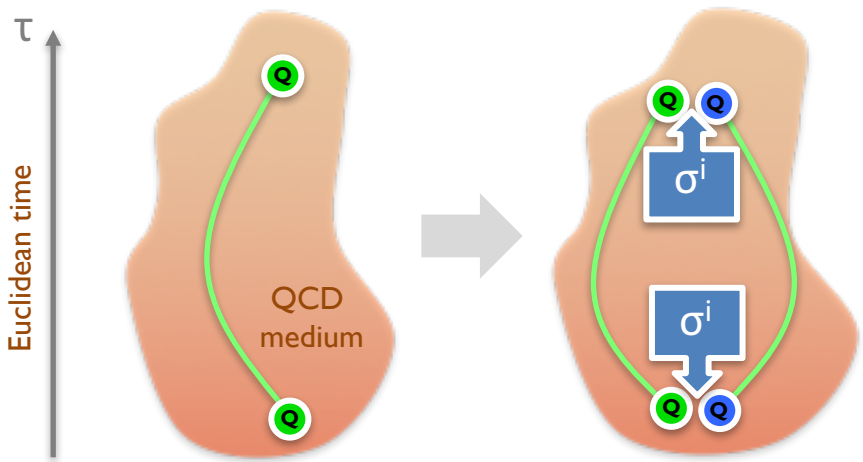
Davies, Thacker Phys.Rev. D45 (1992)

QQ propagator
projected to a certain channel

„correlator of QQ wavefct.
$D_{J/\psi}(\tau) \mathrel{\hat{=}} \langle \psi_{J/\psi}(\tau) \psi^{\dagger}_{J/\psi}(0) \rangle$ "

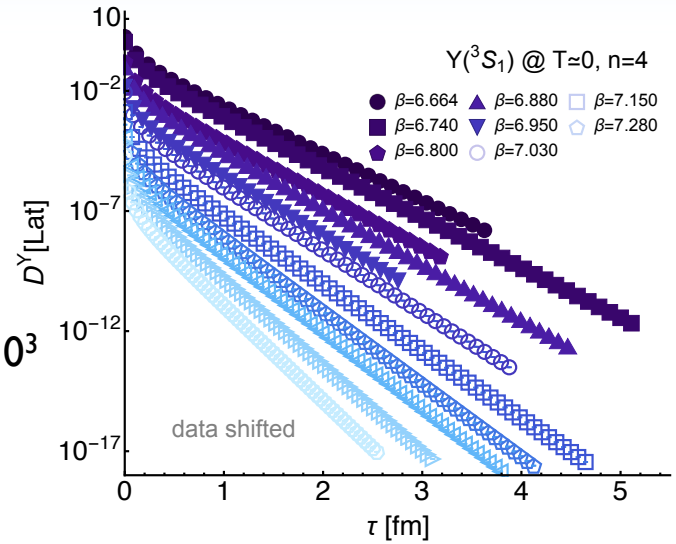
Brambilla et. al. Rev.Mod.Phys. 77 (2005) 1423

Correlation functions in NRQCD



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

$N_{bb}^{meas}(T>0)=1\text{-}4\times10^3$



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

Non-rel. propagator of a single heavy quark G

Davies, Thacker Phys.Rev. D45 (1992)

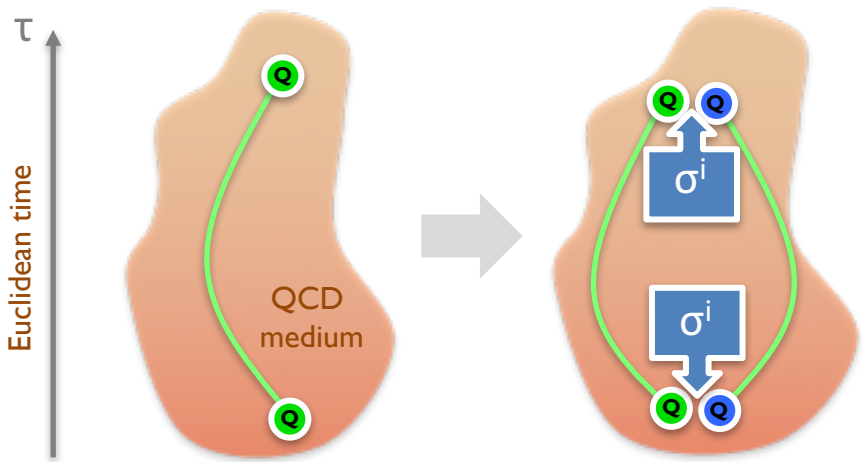
QQ propagator projected to a certain channel

„correlator of QQ wavefct.

$D_{J/\psi}(\tau) \mathrel{\hat{=}} \langle \psi_{J/\psi}(\tau)\psi^{\dagger}_{J/\psi}(0)\rangle$ "

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

Correlation functions in NRQCD

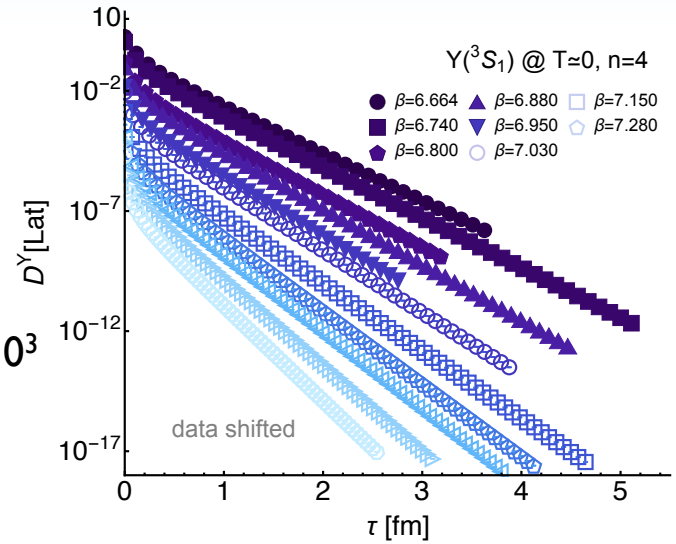


$N_{bb}^{meas}(T=0)=400$

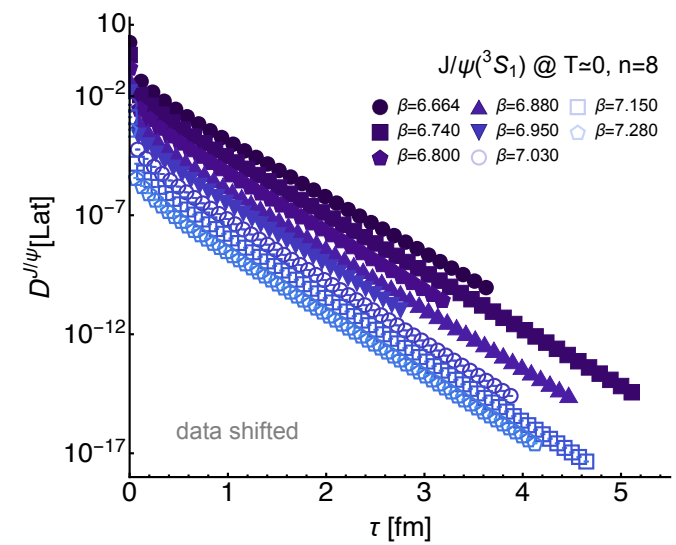
$N_{bb}^{meas}(T>0)=1\text{-}4\times10^3$

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

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



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



Non-rel. propagator of a single heavy quark G

Davies, Thacker Phys.Rev. D45 (1992)

QQ propagator projected to a certain channel

„correlator of QQ wavefct.

$D_{J/\psi}(\tau) \mathrel{\hat{=}} \langle \psi_{J/\psi}(\tau)\psi^{\dagger}_{J/\psi}(0)\rangle$ "

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

An improved Bayesian strategy

- In NRQCD simulation data D and spectral function ρ are related via Laplace transform

$$D(\tau) = \int_{-2M_Q}^{\infty} d\omega e^{-\tau\omega} \rho(\omega)$$

An improved Bayesian strategy

- In NRQCD simulation data D and spectral function ρ are related via Laplace transform

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

  - **Improvement:** incorporate both Euclidean and imaginary frequency data in unfolding
  - **Ill-posed problem:** naïve χ^2 fit of spectrum leads to degenerate solutions

An improved Bayesian strategy

- In NRQCD simulation data D and spectral function ρ are related via Laplace transform

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

  - **Improvement:** incorporate both Euclidean and imaginary frequency data in unfolding
  - **Ill-posed problem:** naïve χ^2 fit of spectrum leads to degenerate solutions
- Bayesian strategy: regulate χ^2 fit (likelihood L) with prior information (regulator S)

An improved Bayesian strategy

- In NRQCD simulation data D and spectral function ρ are related via Laplace transform

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

  - **Improvement:** incorporate both Euclidean and imaginary frequency data in unfolding
  - **Ill-posed problem:** naïve χ^2 fit of spectrum leads to degenerate solutions

- Bayesian strategy: regulate χ^2 fit (likelihood L) with prior information (regulator S)

Standard BR method (BRFT)

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

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

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

An improved Bayesian strategy

- In NRQCD simulation data D and spectral function ρ are related via Laplace transform

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

  - **Improvement:** incorporate both Euclidean and imaginary frequency data in unfolding
  - **Ill-posed problem:** naïve χ^2 fit of spectrum leads to degenerate solutions

- Bayesian strategy: regulate χ^2 fit (likelihood L) with prior information (regulator S)

Standard BR method (BRFT)

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

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

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

New **low ringing BR method**

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

- 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

A.R. in preparation

An improved Bayesian strategy

- In NRQCD simulation data D and spectral function ρ are related via Laplace transform

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

  - **Improvement:** incorporate both Euclidean and imaginary frequency data in unfolding
  - **Ill-posed problem:** naïve χ^2 fit of spectrum leads to degenerate solutions

- Bayesian strategy: regulate χ^2 fit (likelihood L) with prior information (regulator S)

Standard BR method (BRFT)

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

- 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**

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

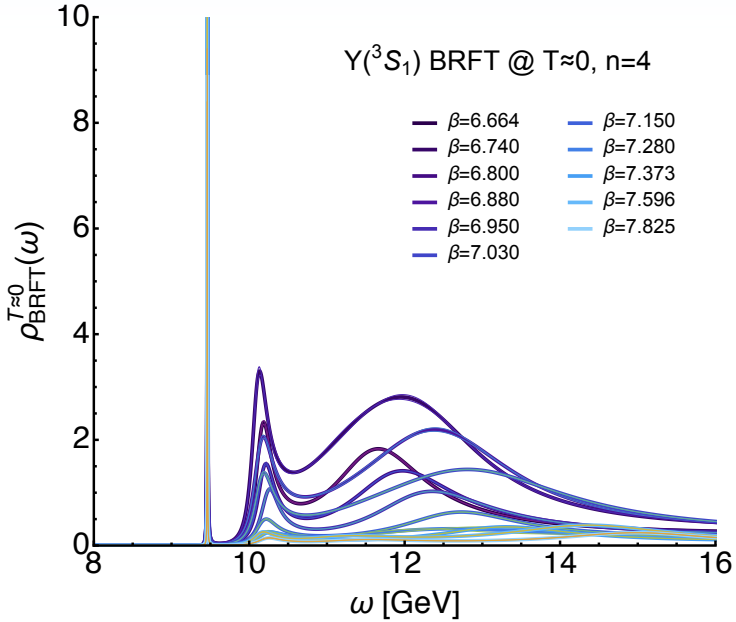
- Introduces penalty on arc length of reconstruction $(dL/dw)^2 = 1 + (d\rho/dw)^2$
- Efficiently removes ringing but may lead to overestimated peak widths

„low gain – low noise“

A.R. in preparation

Calibrating Bayesian spectra at T=0

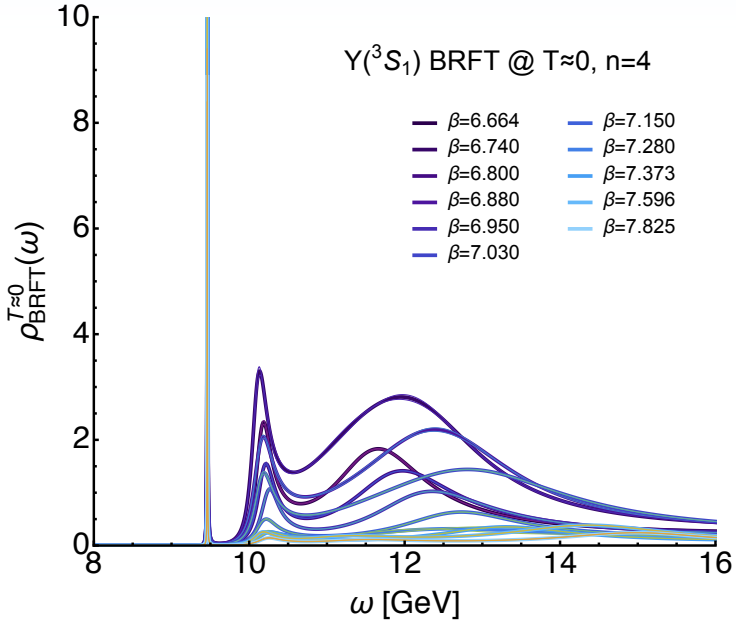
S.Kim, P.Petreczky, A.R. in preparation

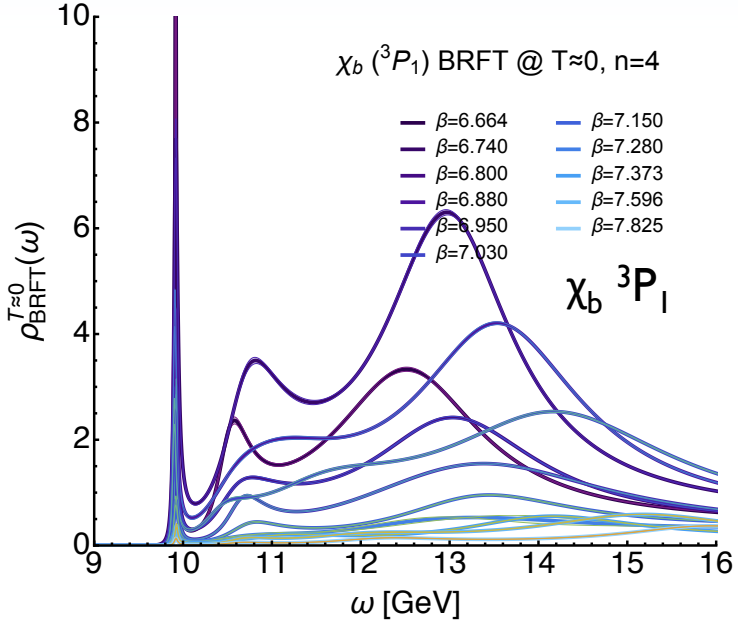


m_Υ from PDG to calibrate absolute freq. scale

Calibrating Bayesian spectra at T=0

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



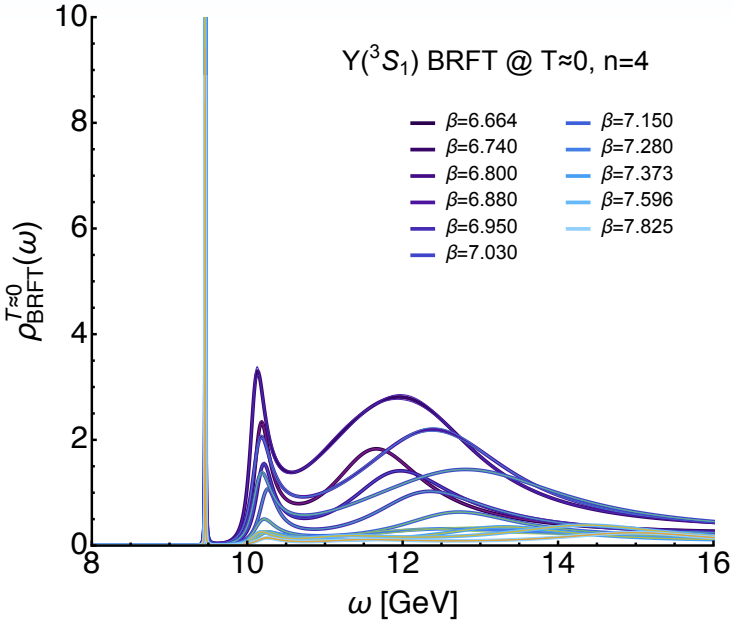


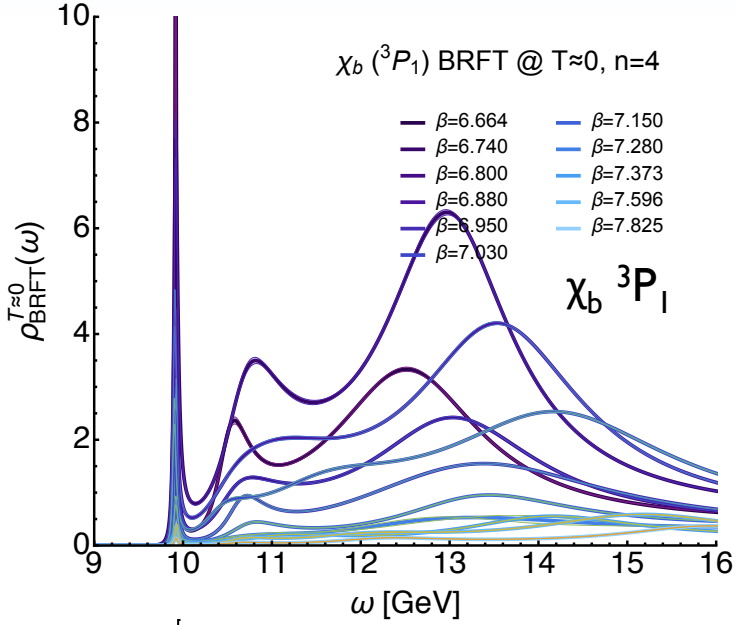
m_Υ from PDG to calibrate absolute freq. scale

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

Calibrating Bayesian spectra at T=0

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

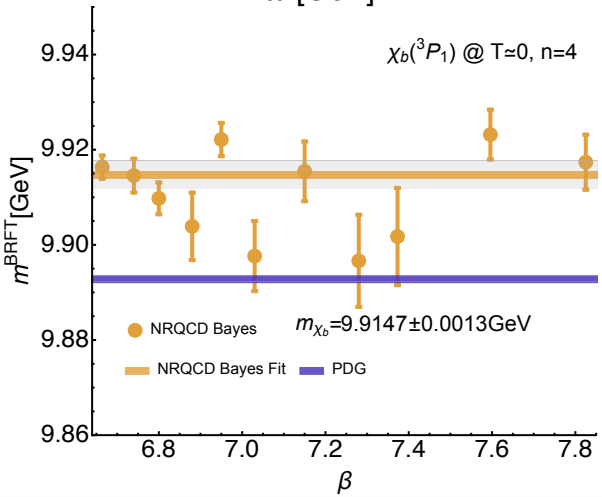




m_Υ from PDG to calibrate absolute freq. scale

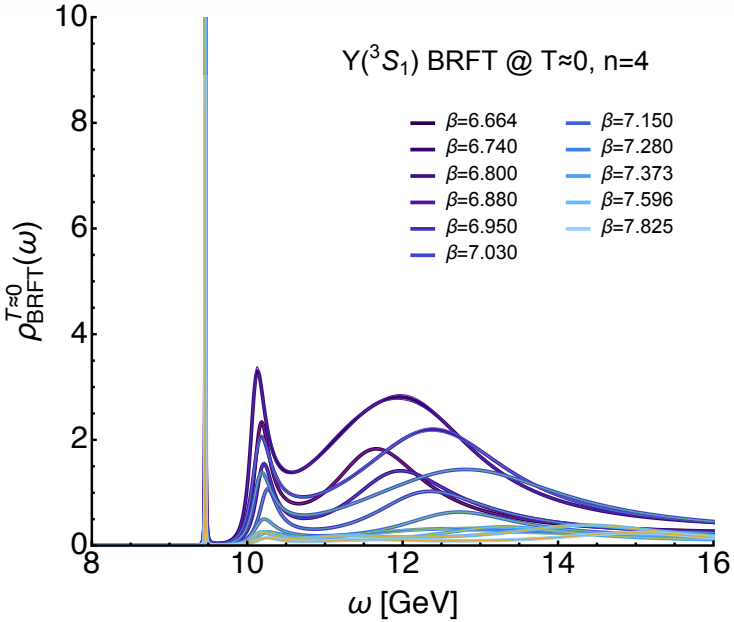
- Check systematic error of lattice computation by postdiction of P-wave ground state mass

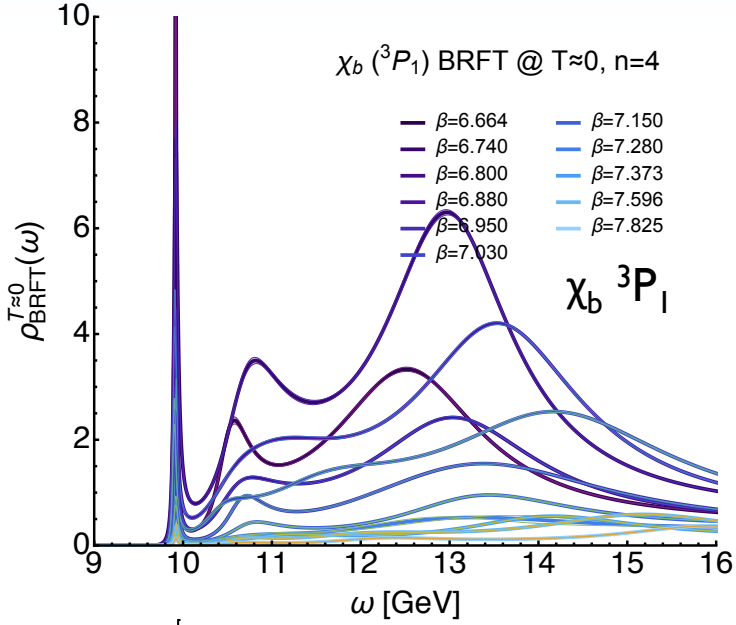
$M^{NRQCD}_{\chi b1}$=9.9147(13) GeV $M^{PDG}_{\chi b1}$=9.89278(3) GeV



Calibrating Bayesian spectra at T=0

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



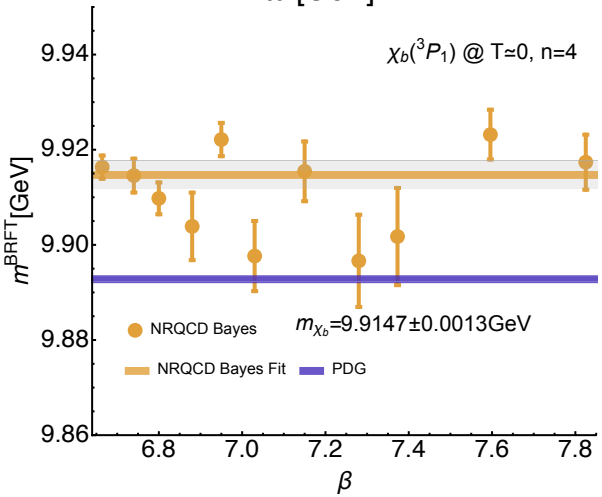


m_Υ from PDG to calibrate absolute freq. scale

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

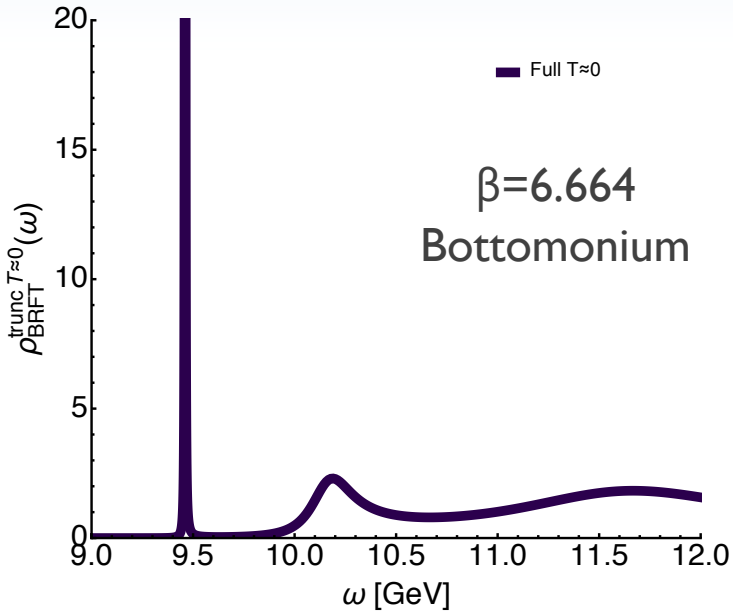
$M^{NRQCD}_{\chi b1}$=9.9147(13) GeV $M^{PDG}_{\chi b1}$=9.89278(3) GeV

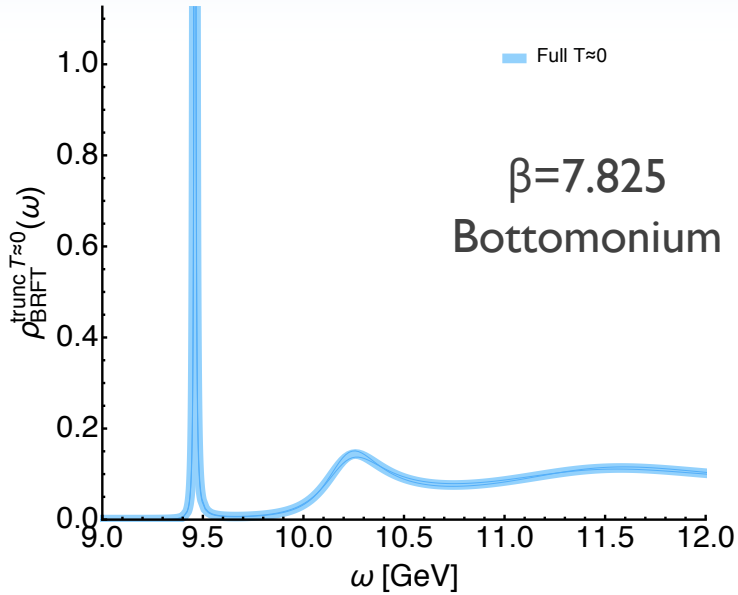
$M^{NRQCD}_{\chi c1}$=3.5086(39) GeV $M^{PDG}_{\chi c1}$=3.51066(7) GeV



Taking control of systematics I

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

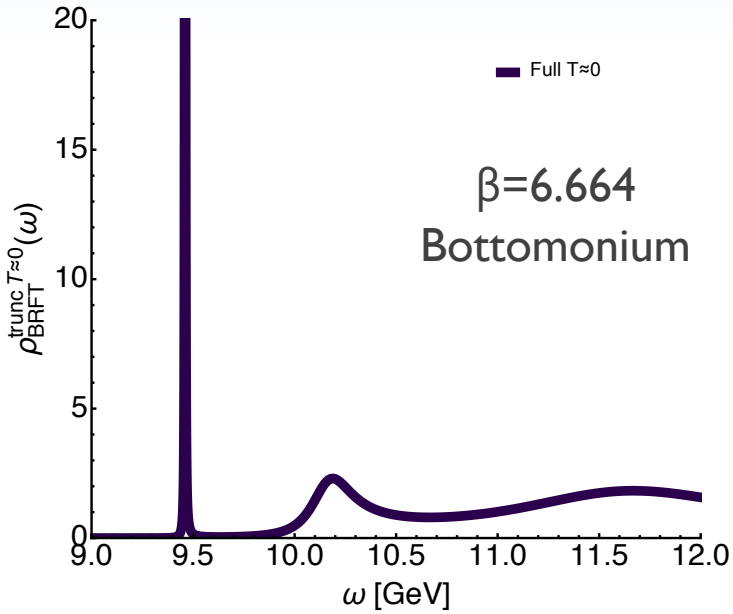


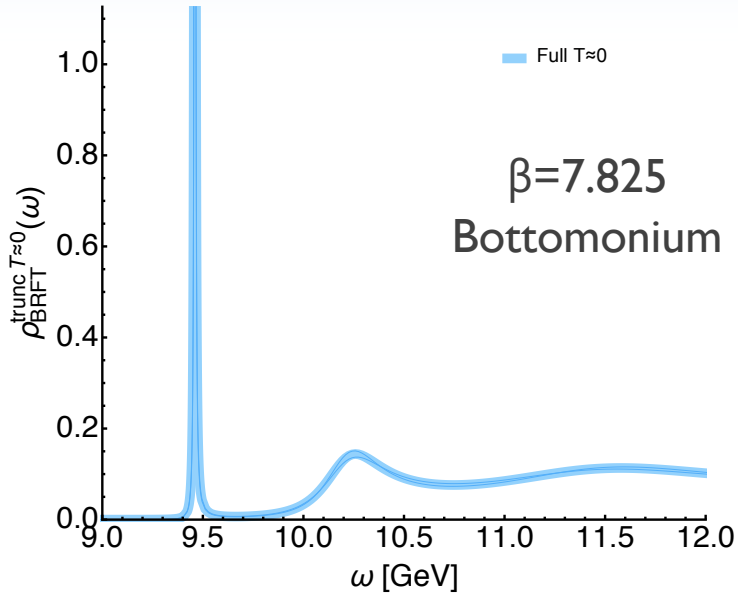


- The “high-gain” BR method resolves the T=0 ground state very well from N_τ=48-64 points

Taking control of systematics I

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

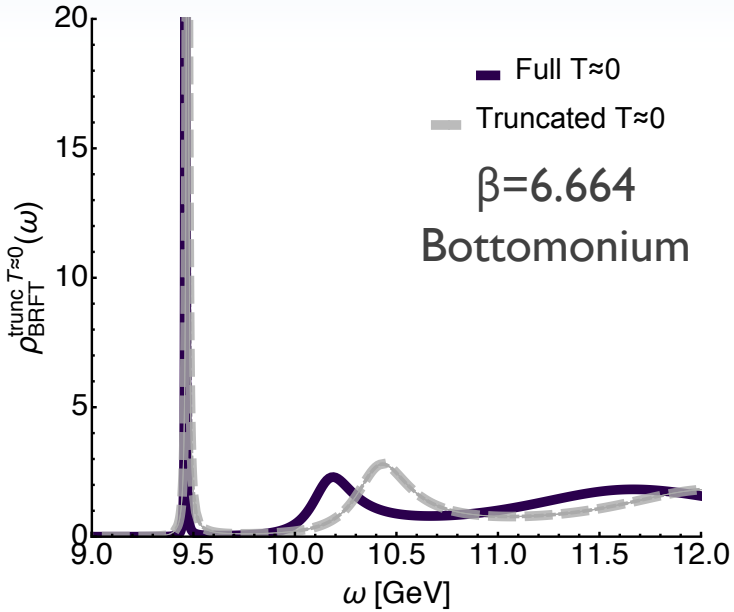




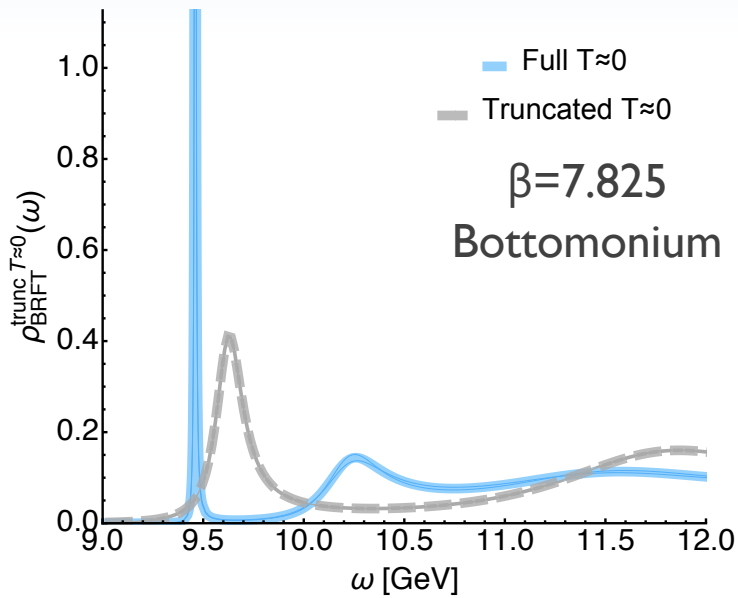
- The "high-gain" BR method resolves the T=0 ground state very well from N_τ=48-64 points
- How does accuracy suffer from limited available information at T>0 (N_τ=12) ?

Taking control of systematics I

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



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

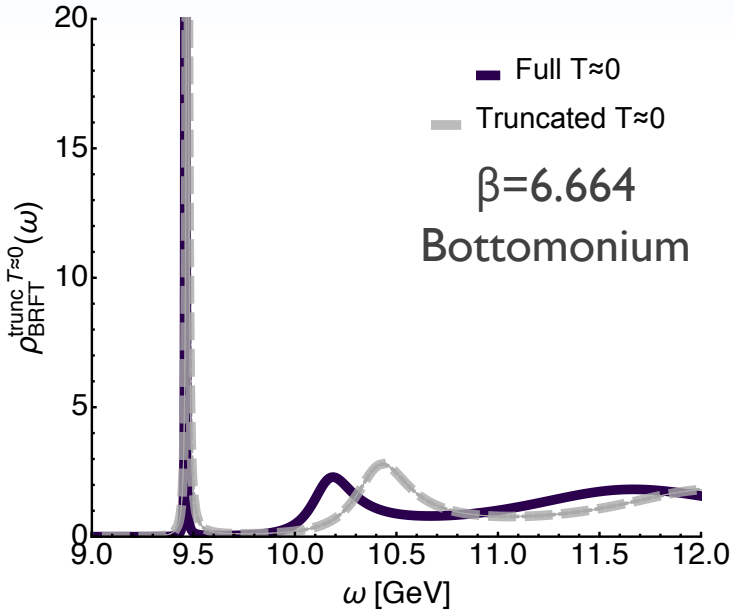


$\Delta M_{7.825}$=159(1)MeV

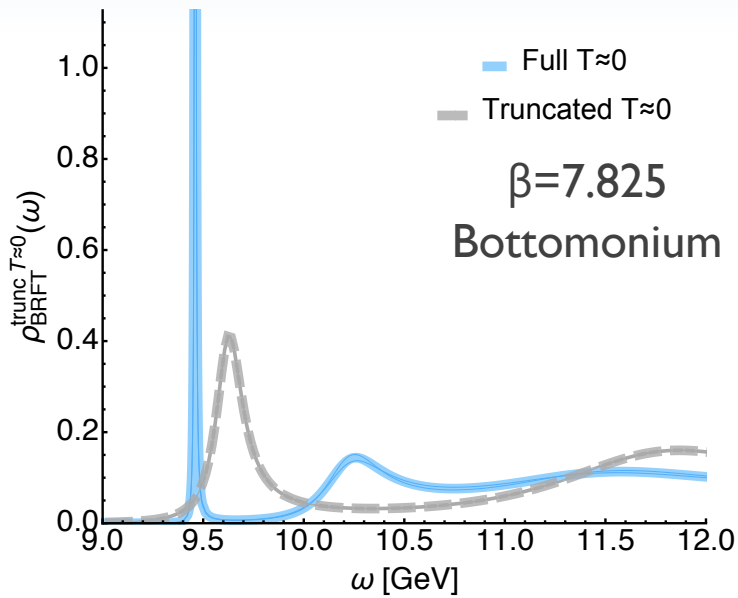
- The "high-gain" BR method resolves the T=0 ground state very well from N_τ=48-64 points
- How does accuracy suffer from limited available information at T>0 (N_τ=12) ?

Taking control of systematics I

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



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



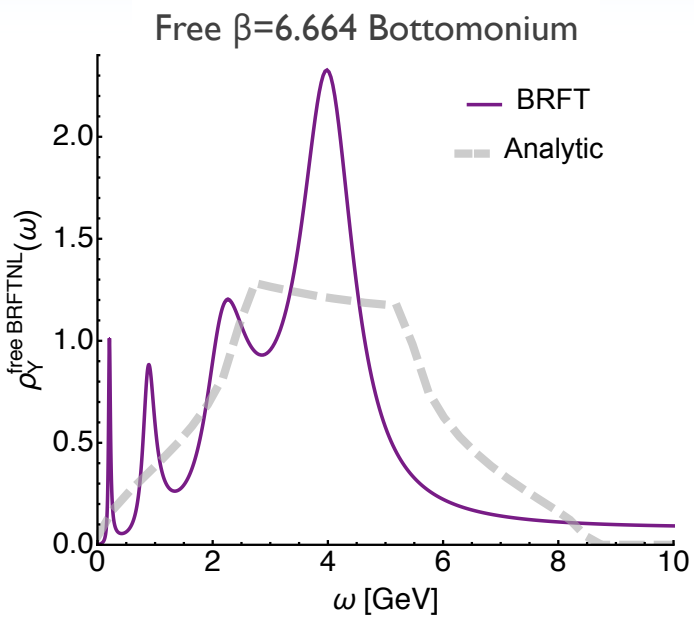
$\Delta M_{7.825}$=159(1)MeV

- 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

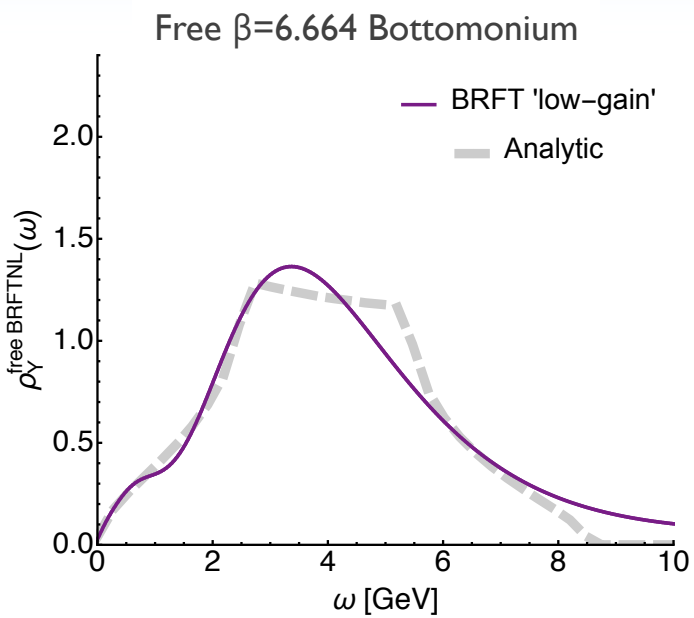
S.Kim, P.Petreczky, A.R. in preparation



- Standard "high-gain" BR on small (N_τ=12) simulation datasets suffers from ringing

Taking control of systematics II

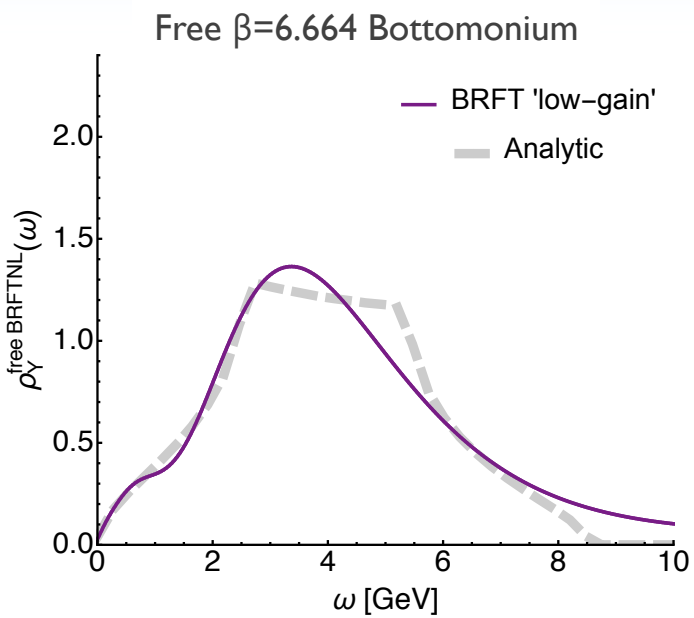
S.Kim, P.Petreczky, A.R. in preparation

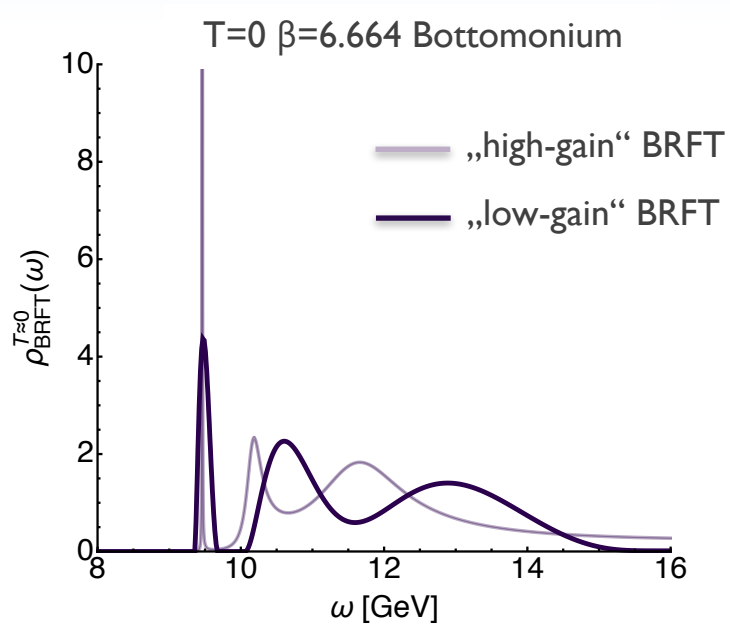


- Standard "high-gain" BR on small (N_τ=12) simulation datasets suffers from ringing
- New "low-gain" BR removes ringing from reconstructed analytic free spectra at low ω

Taking control of systematics II

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

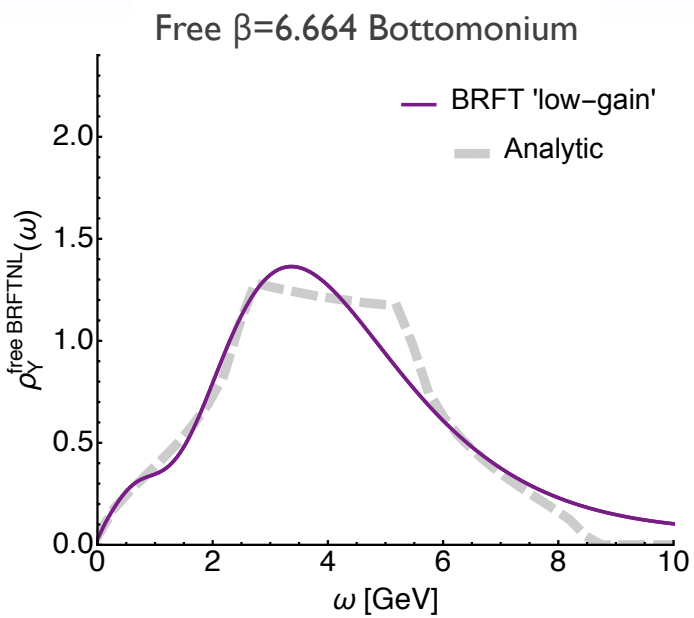


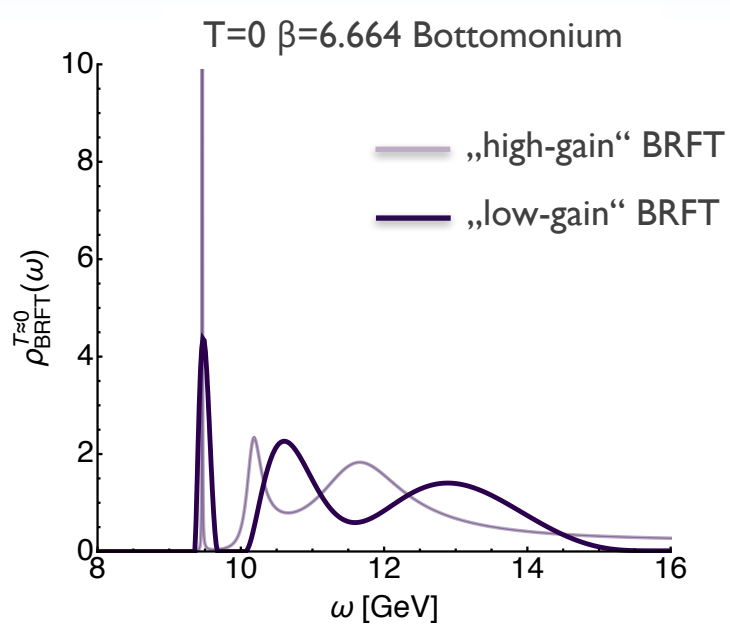


- Standard “high-gain” BR on small (N_τ=12) simulation datasets suffers from ringing
- New “low-gain” BR removes ringing from reconstructed analytic free spectra at low ω
- New ”low-gain” BR method still identifies presence of peaks encoded in data

Taking control of systematics II

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



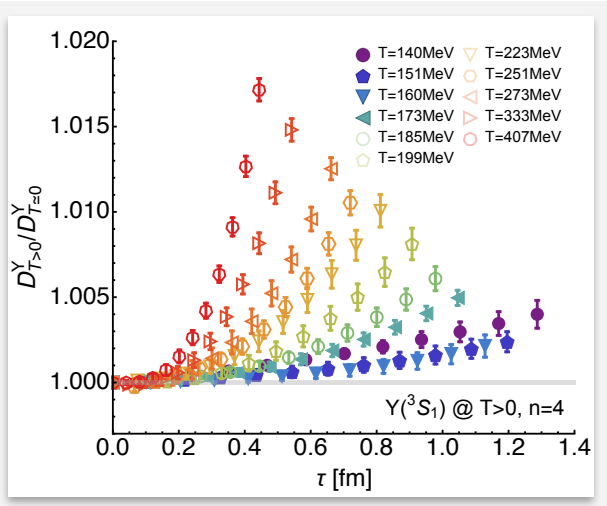


- Standard “high-gain” BR on small (N_τ=12) simulation datasets suffers from ringing
- New “low-gain” BR removes ringing from reconstructed analytic free spectra at low ω
- New ”low-gain” BR method still identifies presence of peaks encoded in data
- Strategy: - Test with “low-gain” reconstruction whether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

Finite temperature results

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

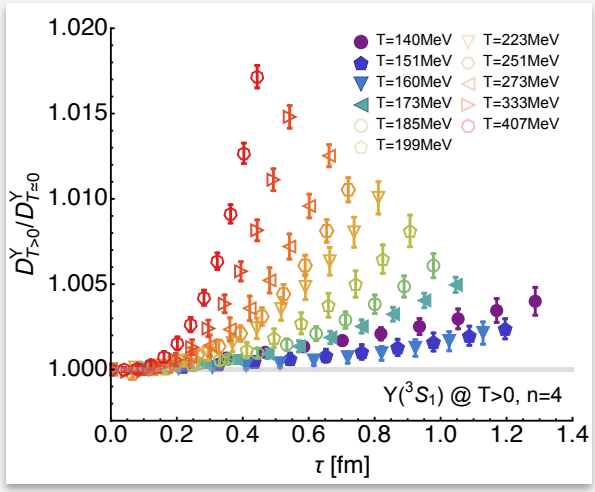
E_{bind} (T=0)~1.1GeV



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

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

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



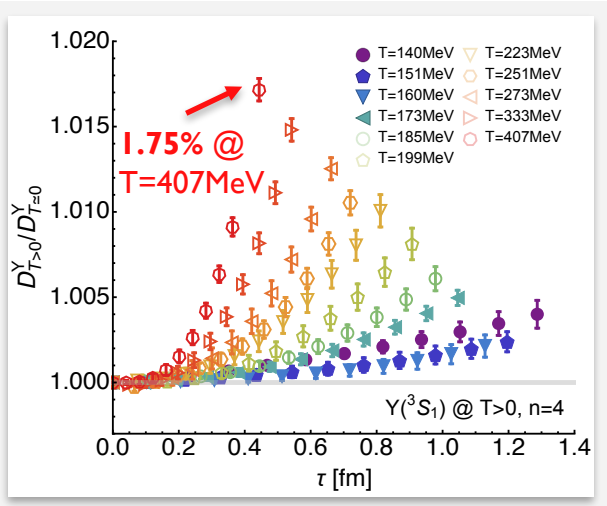
S.Kim, P.Petreczky, A.R. in preparation

- Upsilon shows non-monotonous behavior around $T \sim T_C$

  (bb 3S1 channel contains most excited states)

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

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



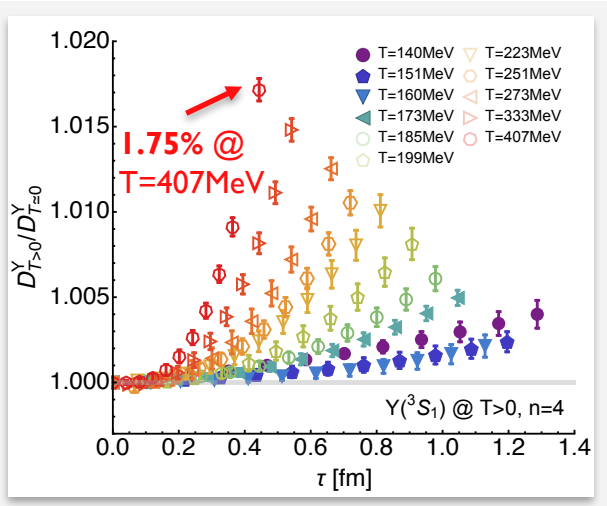
S.Kim, P.Petreczky, A.R. in preparation

- Upsilon shows non-monotonous behavior around T~T_C

  (bb 3S1 channel contains most excited states)

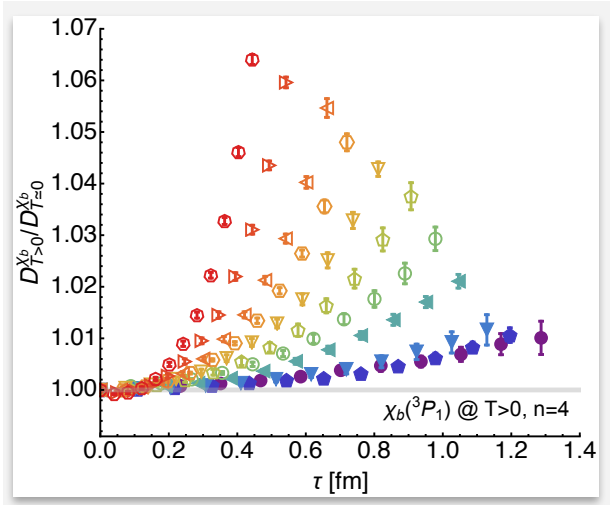
T>0 effects in $Q\bar{Q}$ correlators

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



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

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

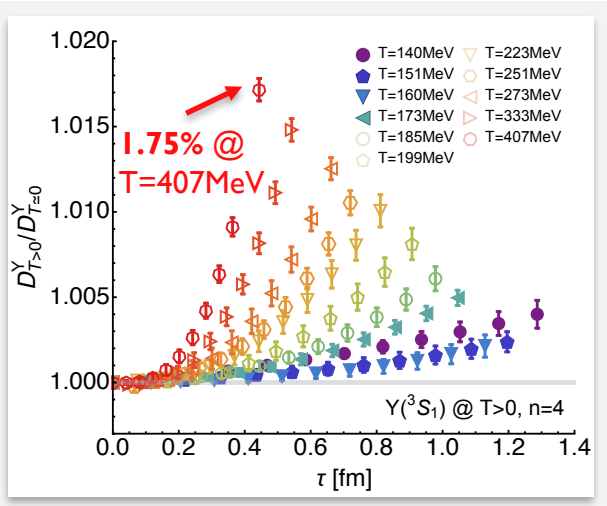


- Upsilon shows non-monotonous behavior around $T \sim T_C$

  (bb 3S1 channel contains most excited states)

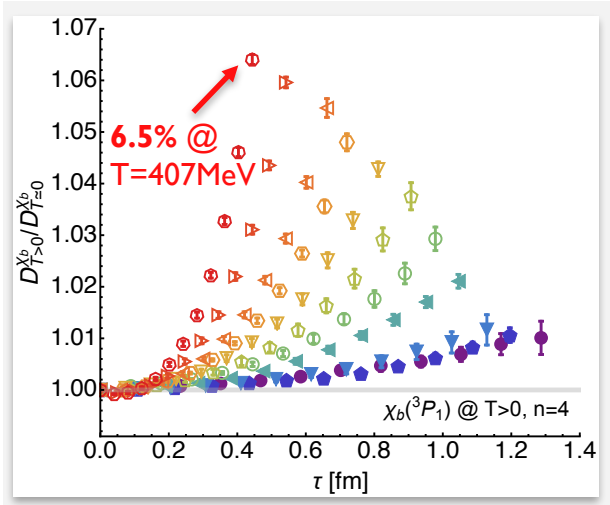
T>0 effects in $Q\bar{Q}$ correlators

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



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

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

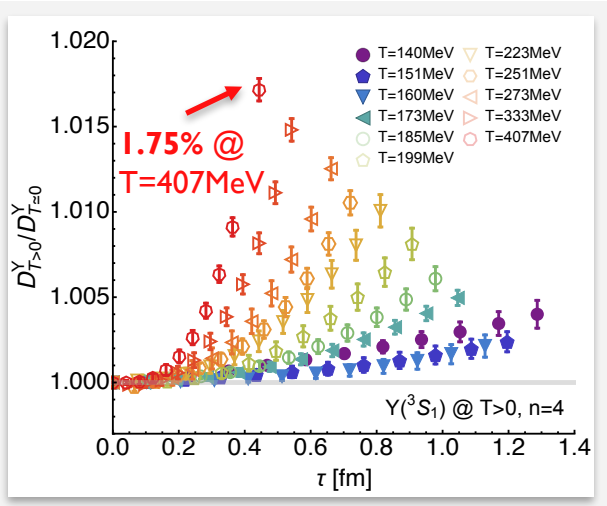


- Upsilon shows non-monotonous behavior around $T \sim T_C$

  (bb 3S1 channel contains most excited states)

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

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

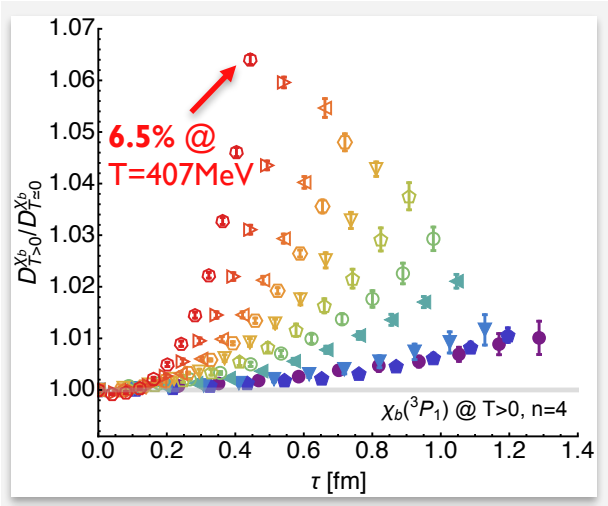


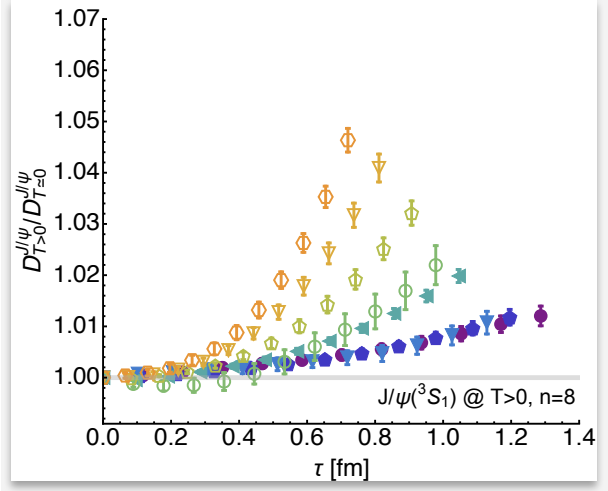
S.Kim, P.Petreczky, A.R. in preparation

- Upsilon shows non-monotonous behavior around T~T_C

(bb 3S1 channel contains most excited states)

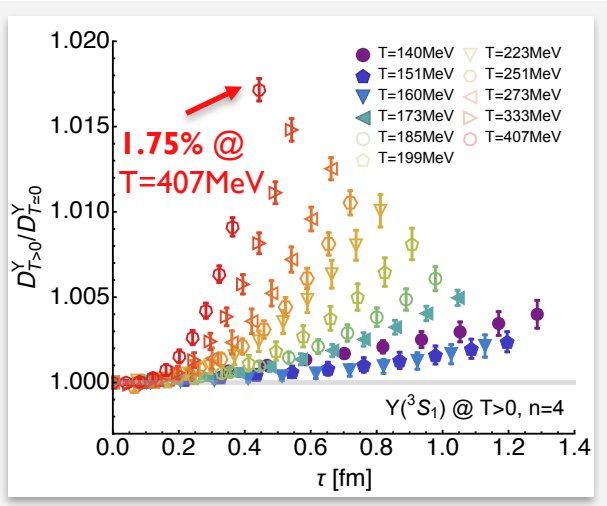
E_{bind} (T=0)~640MeV





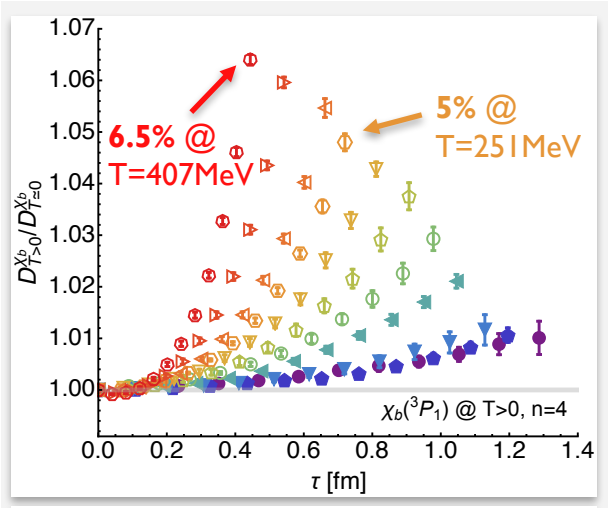
T>0 effects in $Q\bar{Q}$ correlators

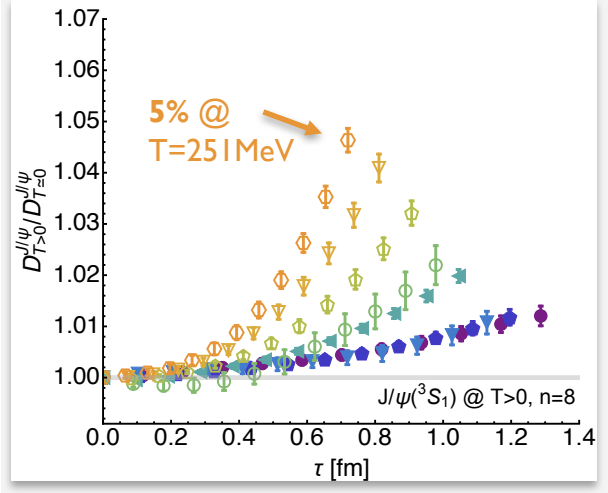
E_{bind} (T=0)~1.1GeV



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

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



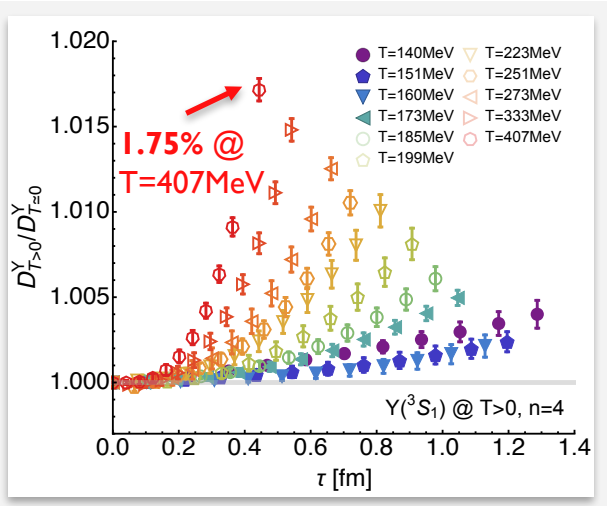


- Upsilon shows non-monotonous behavior around $T \sim T_C$

  (bb 3S1 channel contains most excited states)

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

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

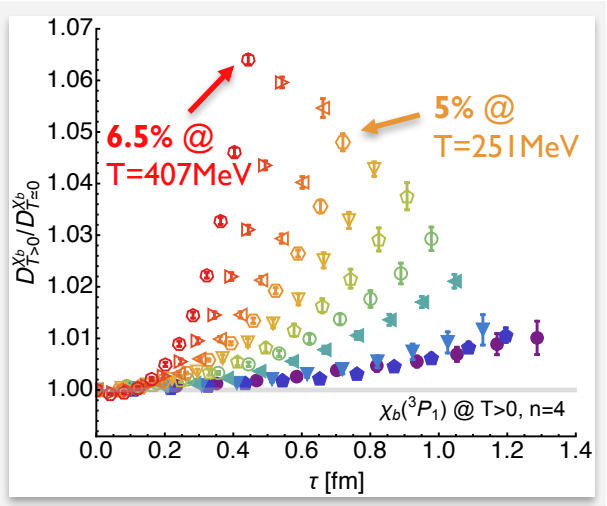


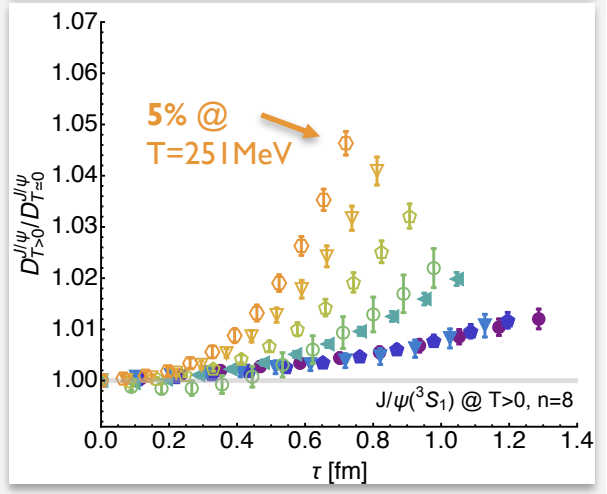
S.Kim, P.Petreczky, A.R. in preparation

- Upsilon shows non-monotonous behavior around $T \sim T_C$

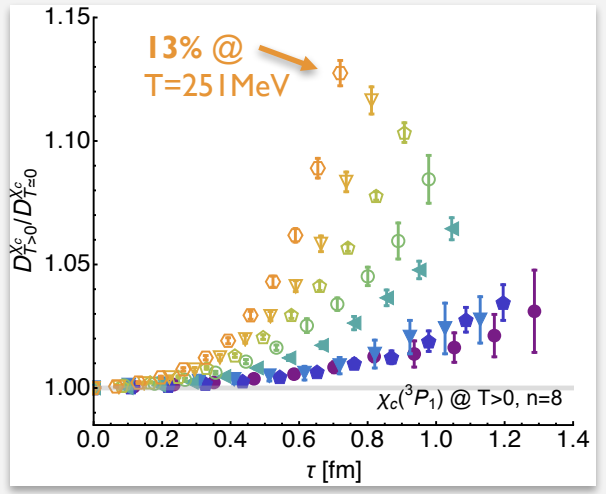
(bb 3S1 channel contains most excited states)

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



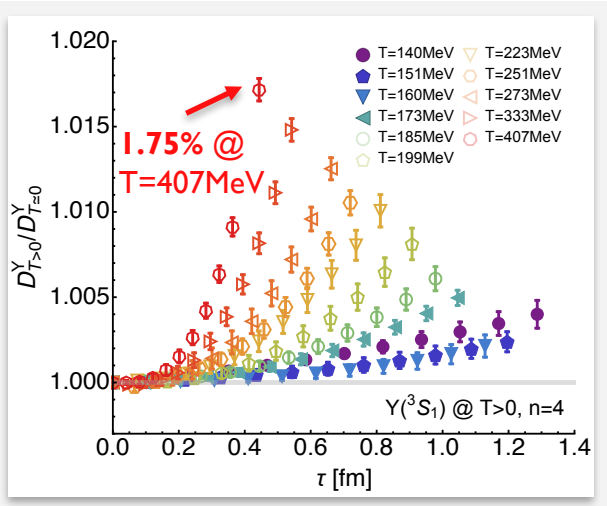


E_{bind} (T=0)~200MeV



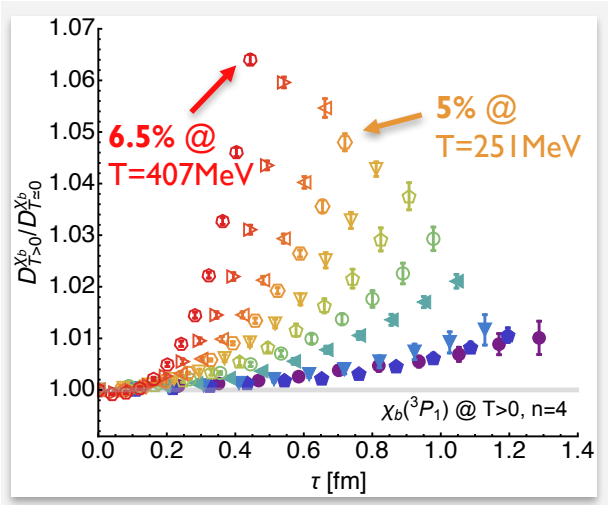
T>0 effects in $Q\bar{Q}$ correlators

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

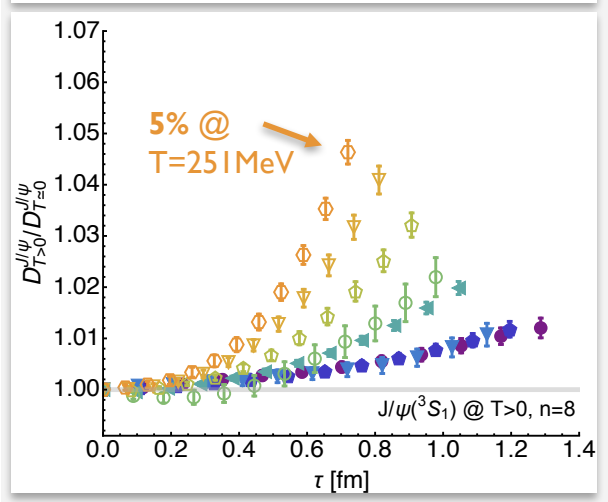


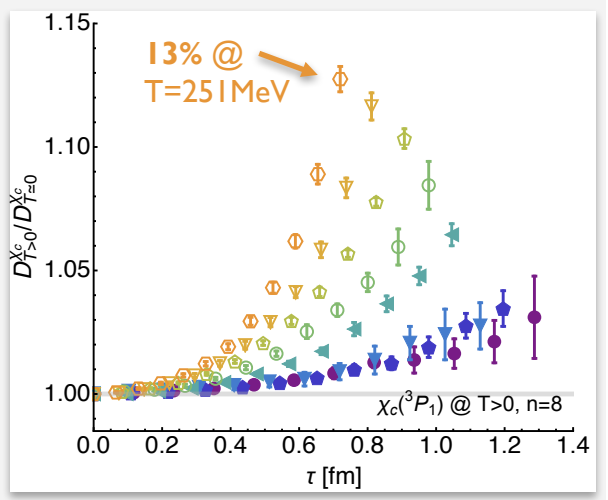
S.Kim, P.Petreczky, A.R. in preparation

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



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

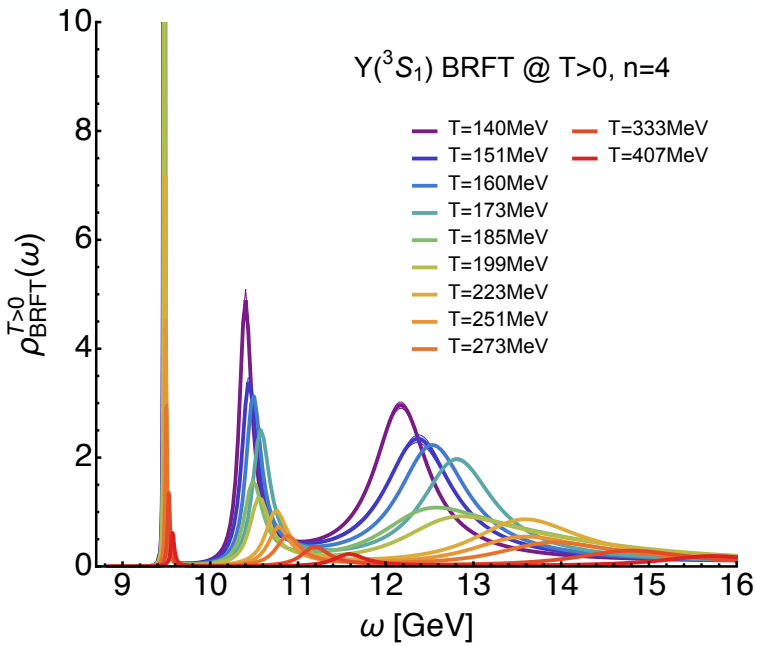


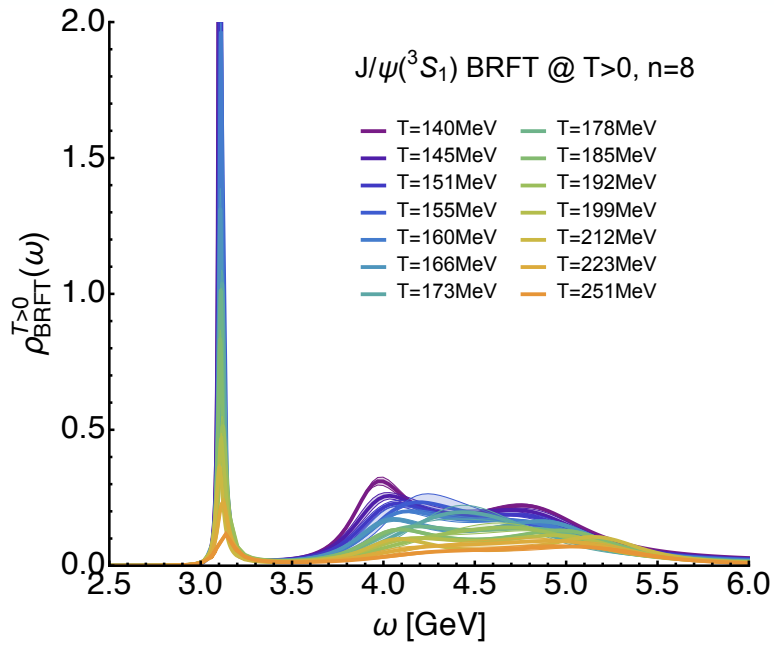


- Upsilon shows non-monotonous behavior around T~T_C
  (bb 3S1 channel contains most excited states)
- Hierarchical T>0 modification w.r.t. vacuum binding energy

NRQCD S-wave spectra at T>0

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

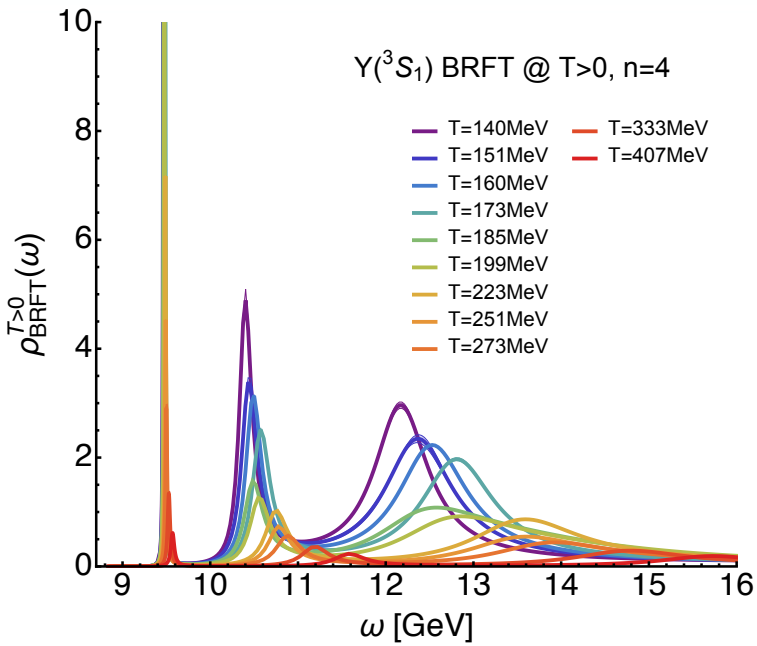


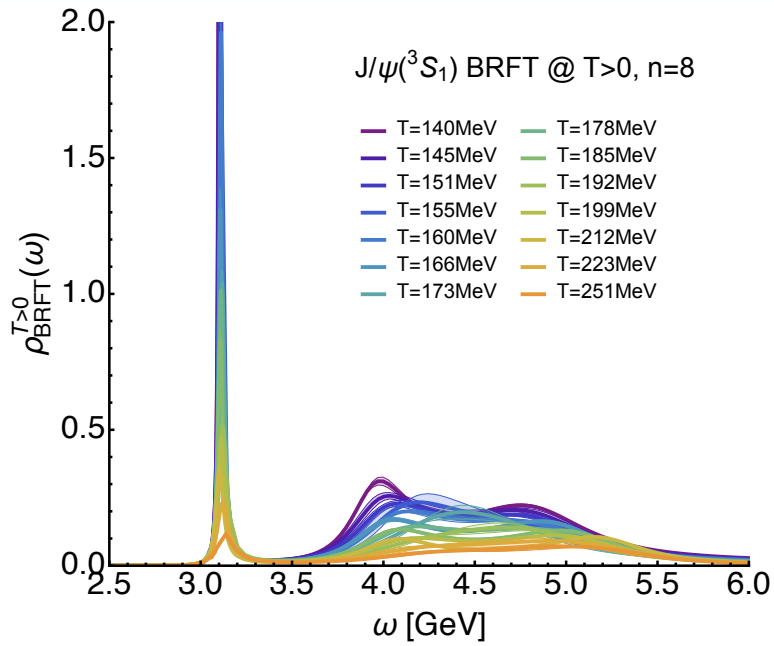


- Ground state well resolved and well separated from higher lying structures

NRQCD S-wave spectra at T>0

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

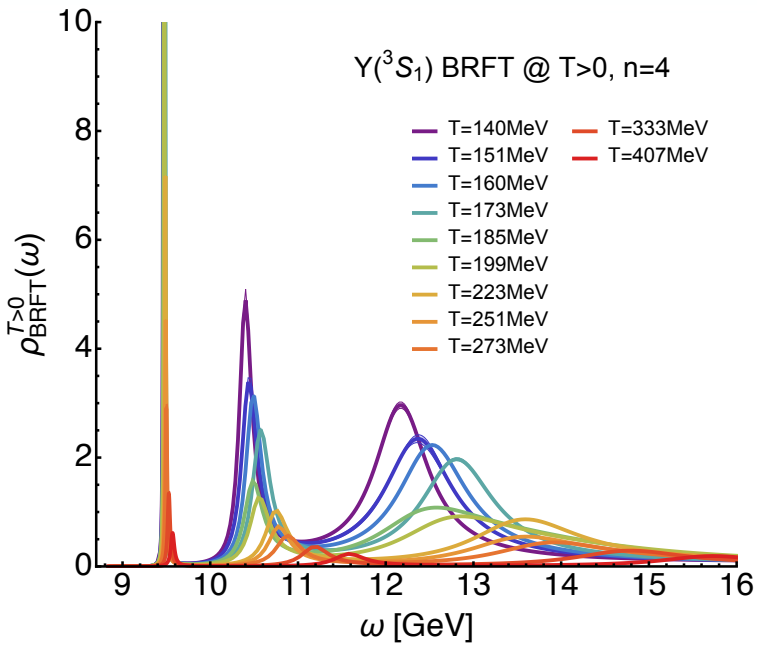


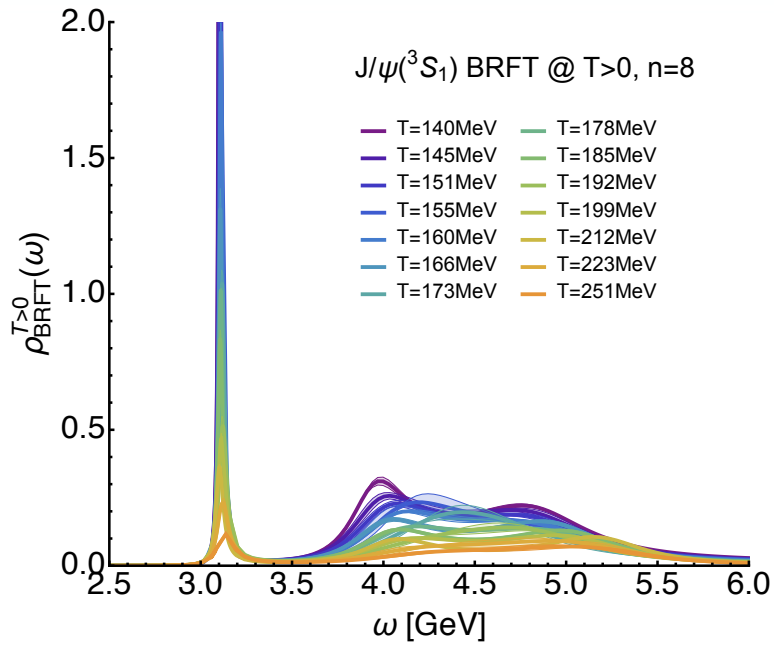


- Ground state well resolved and well separated from higher lying structures
- Combining Euclidean and imaginary frequency data reduces ringing at large ω

NRQCD S-wave spectra at T>0

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

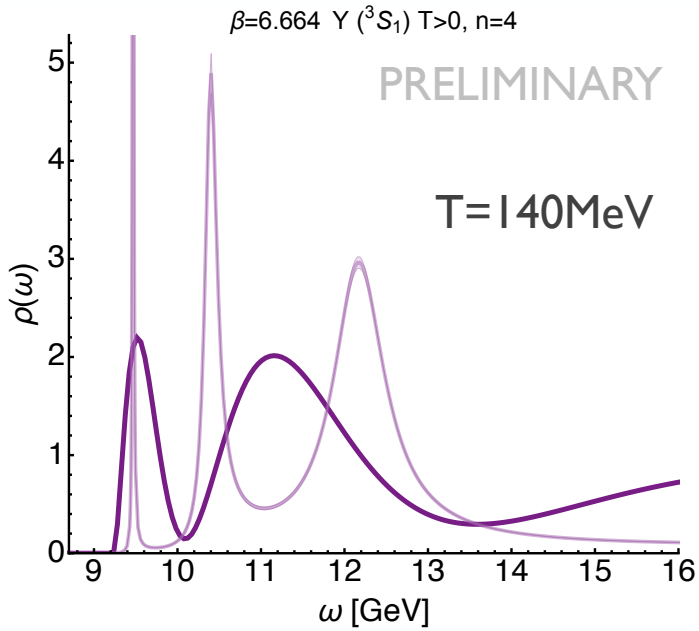


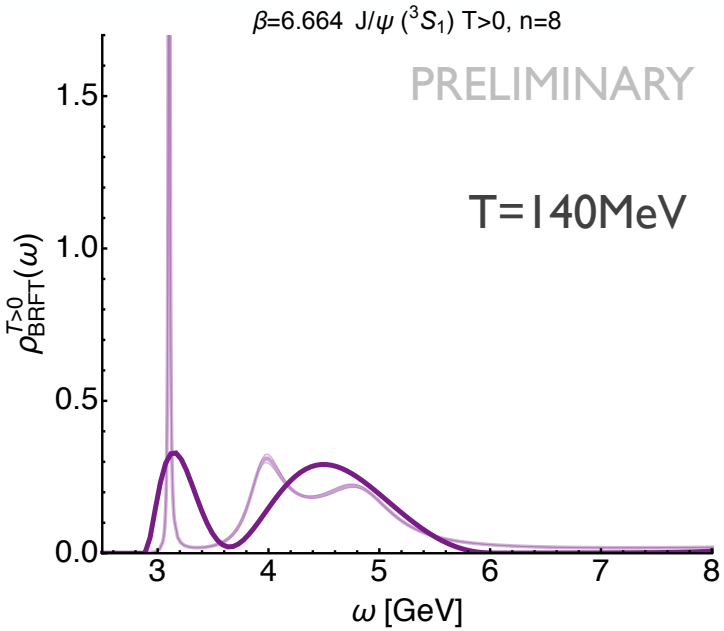


- Ground state well resolved and well separated from higher lying structures
- Combining Euclidean and imaginary frequency data reduces ringing at large ω
- Gradual broadening and shifting of lowest lying peak visible

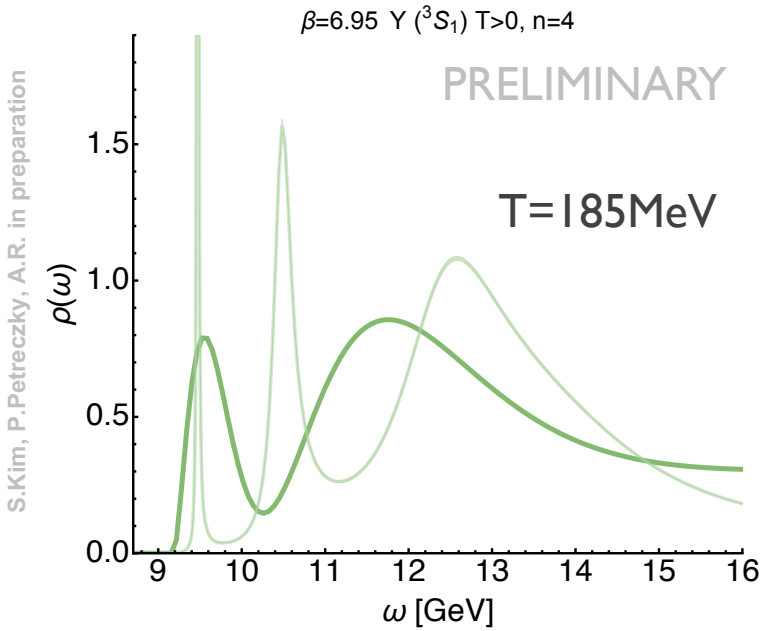
Presence of ground state signals?

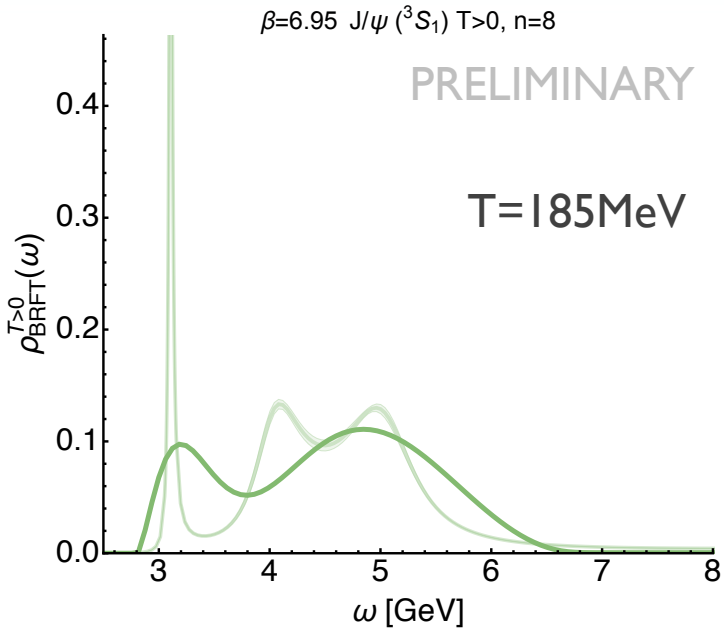
S.Kim, P.Petreczky, A.R. in preparation



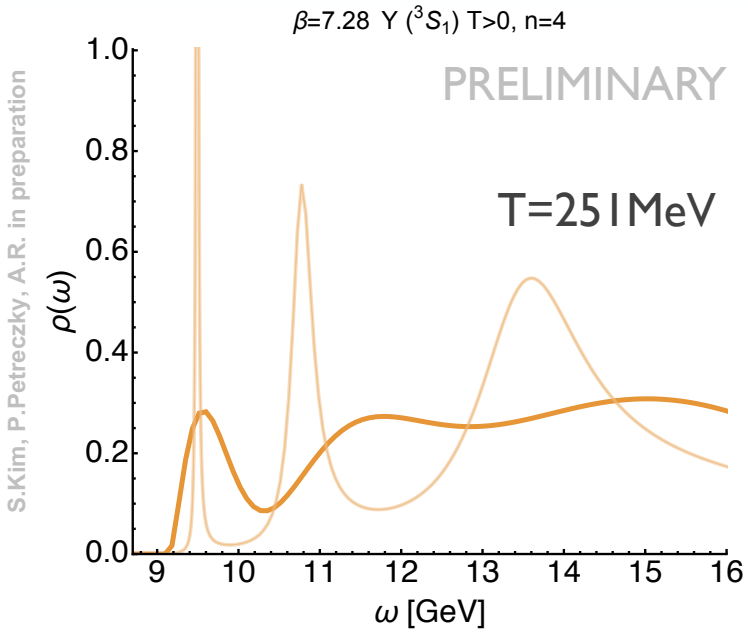


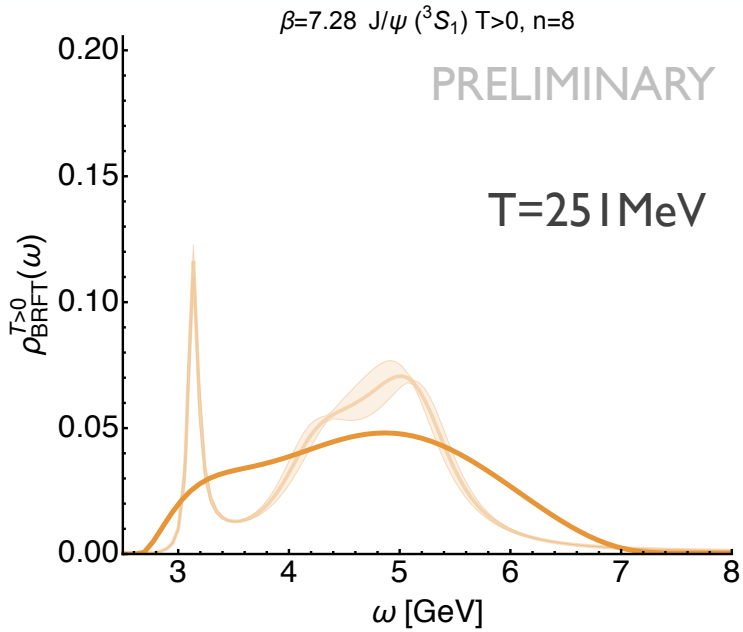
Presence of ground state signals?



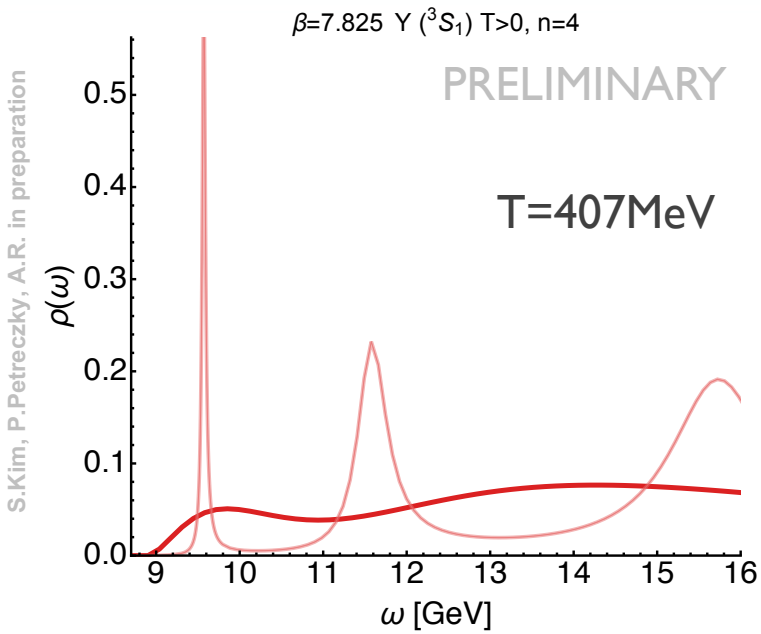


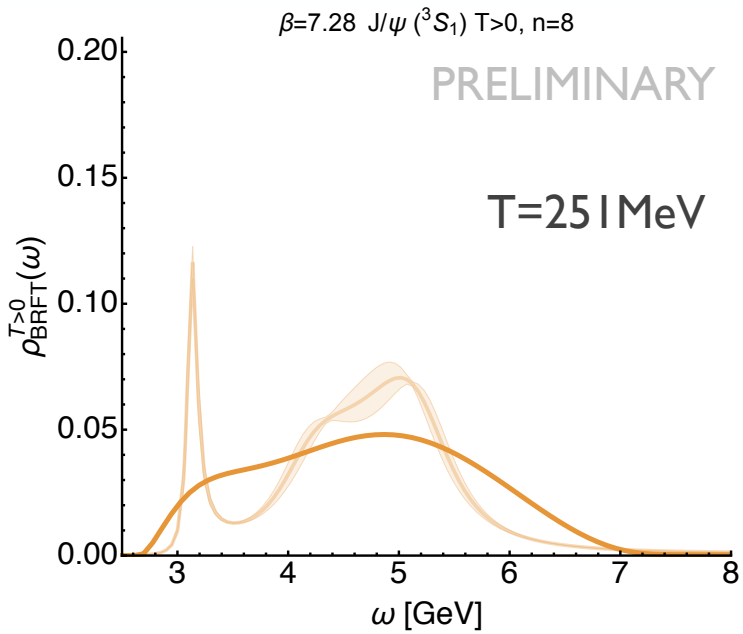
Presence of ground state signals?



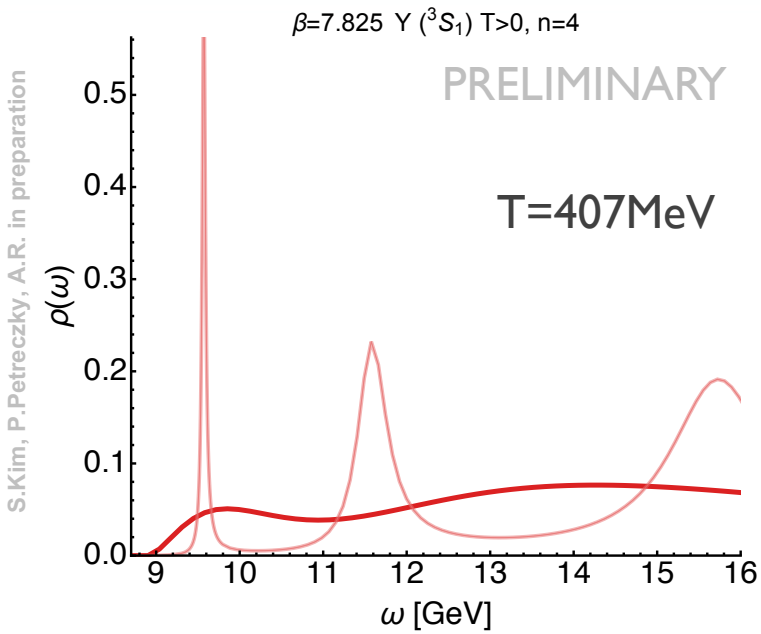


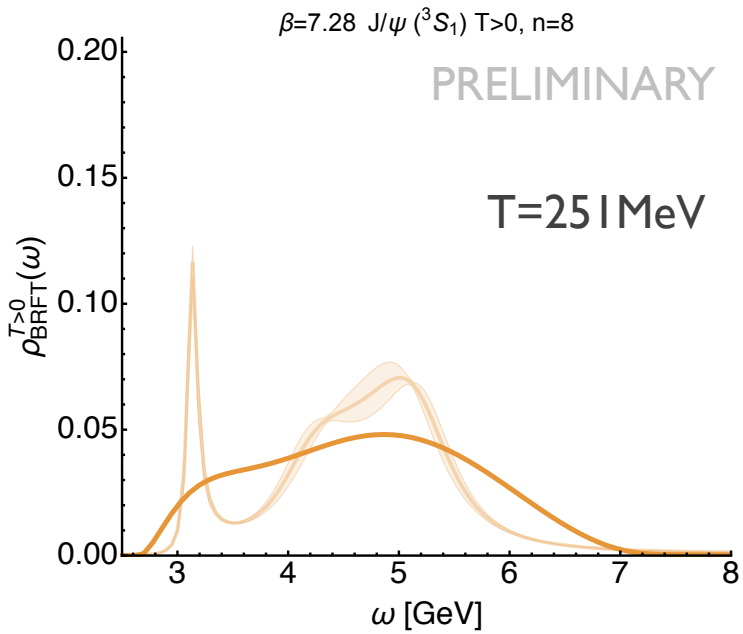
Presence of ground state signals?





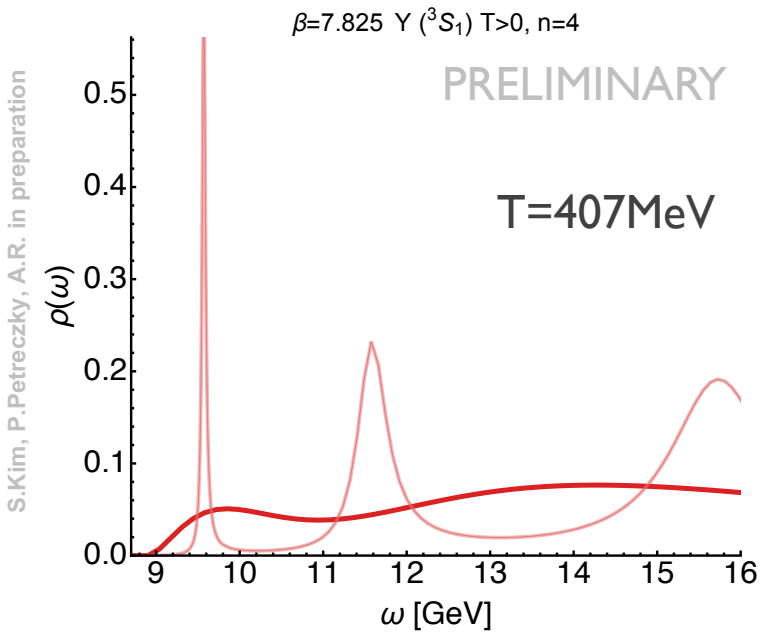
Presence of ground state signals?

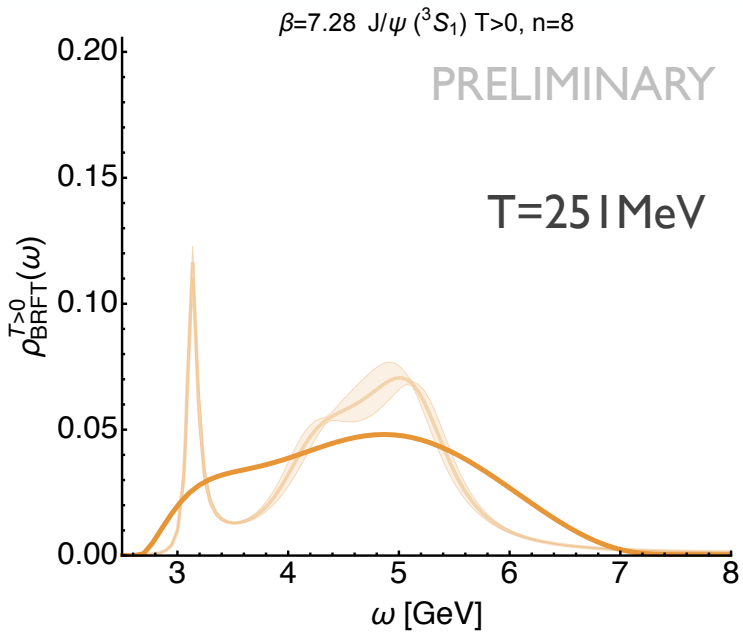




- New “low-gain” BR method shows gradual weakening of ground state signal

Presence of ground state signals?



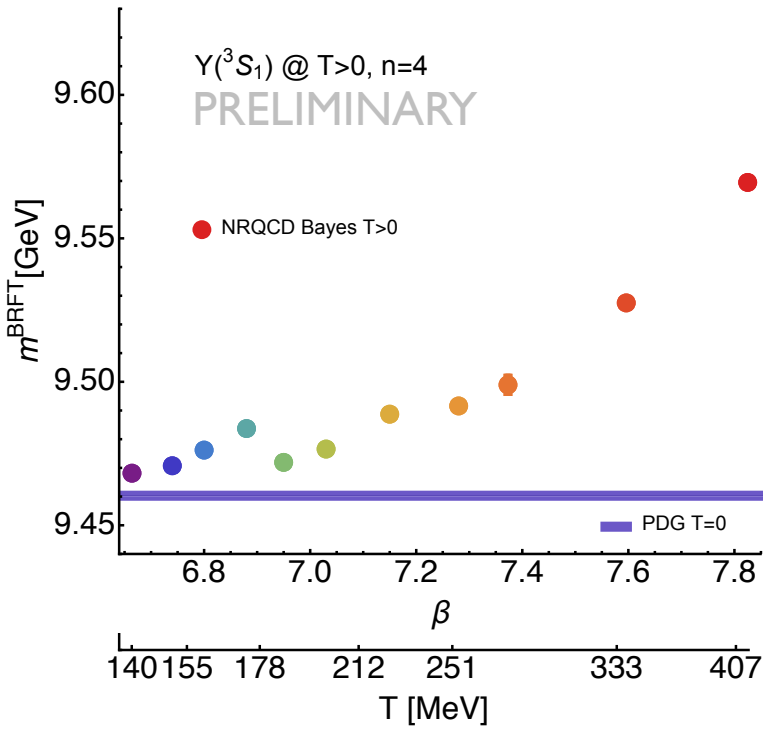


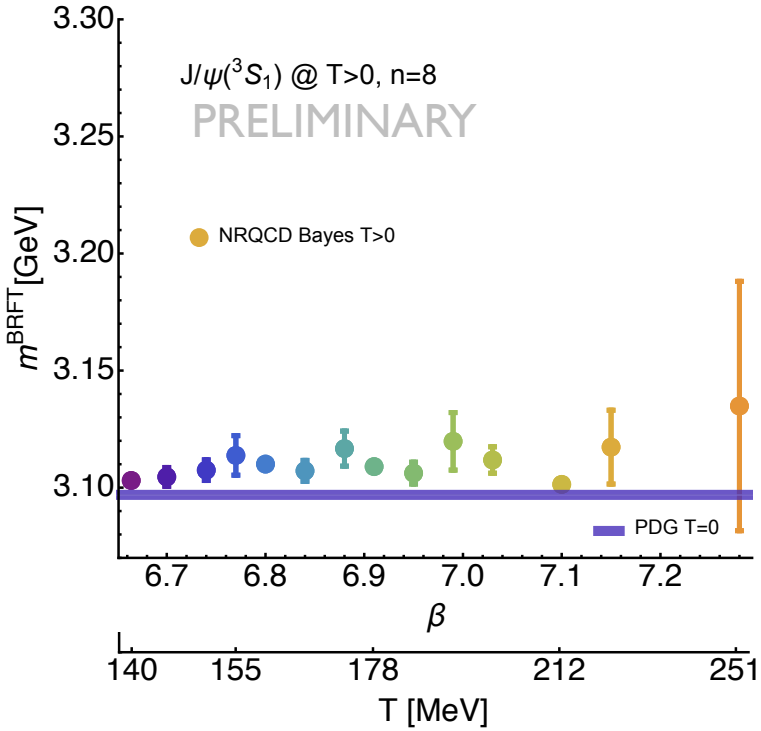
- New "low-gain" BR method shows gradual weakening of ground state signal
- At highest temperature in individual channels: weak ground state remnants remain visible

Upsilon signal up to T=407MeV

Faint J/ψ signal up to T=251MeV

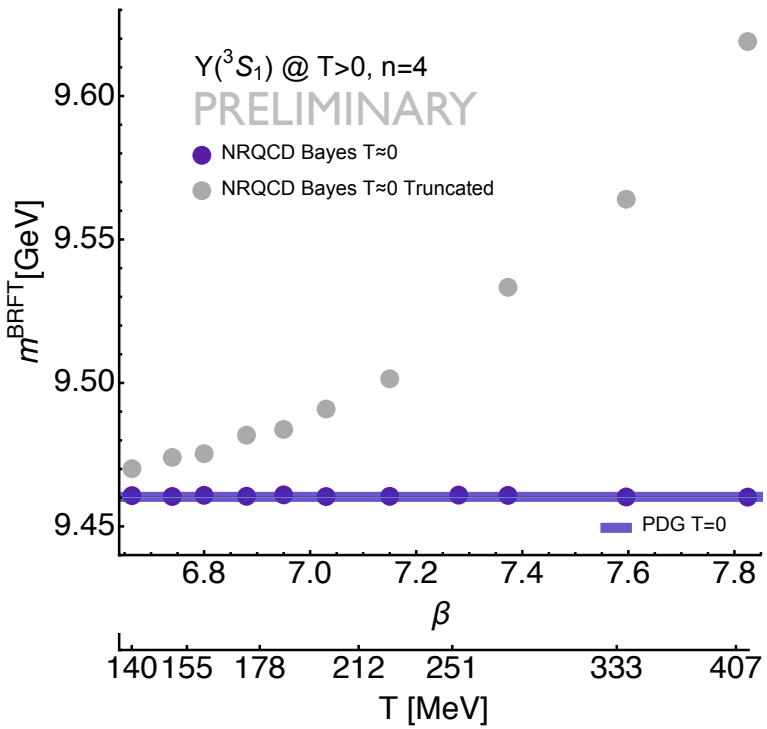
In-medium S-wave mass shifts

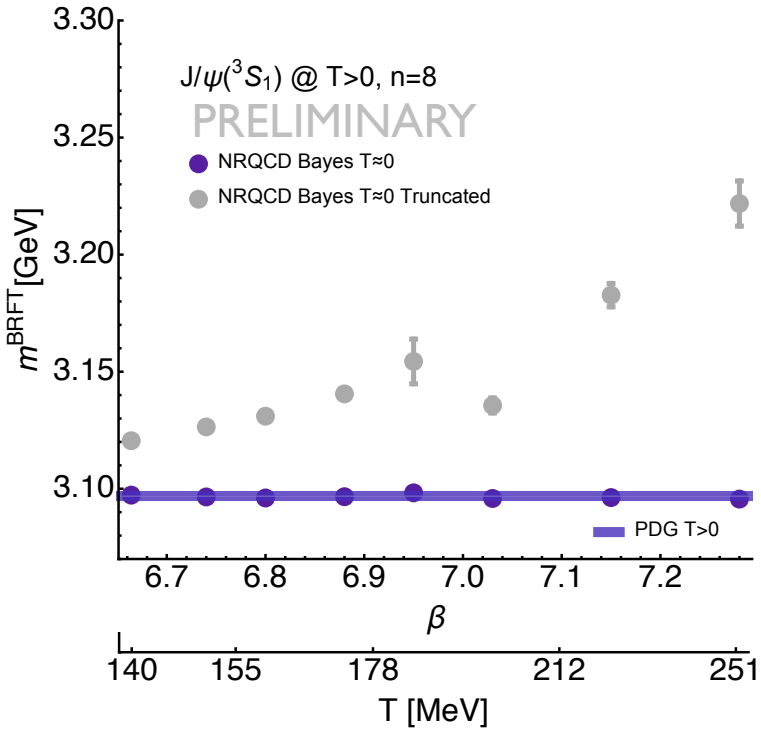




- Naïve inspection of in-medium modification appears to show increasing masses
- BR method systematics: Low number of datapoints introduces shifts to larger masses
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies

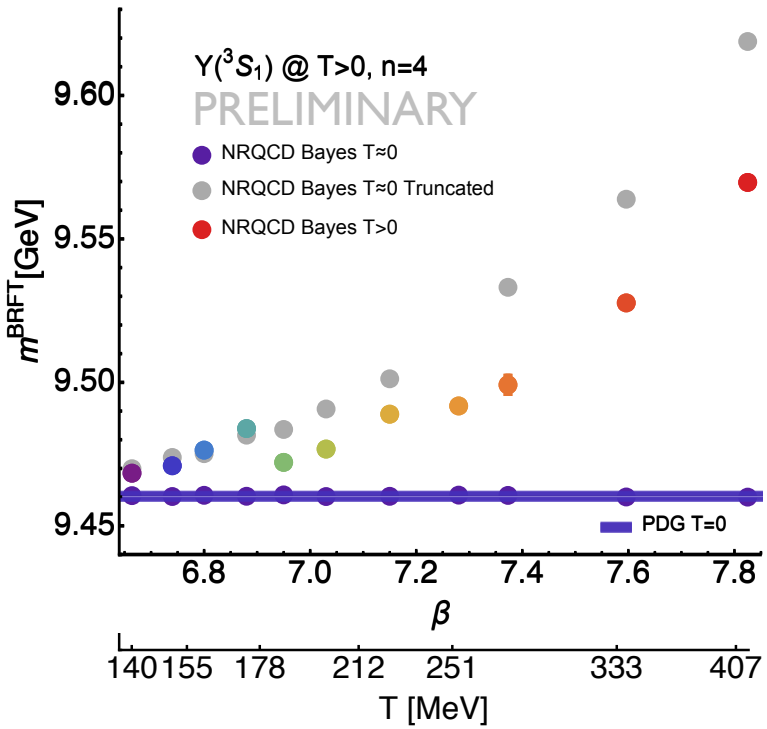
In-medium S-wave mass shifts

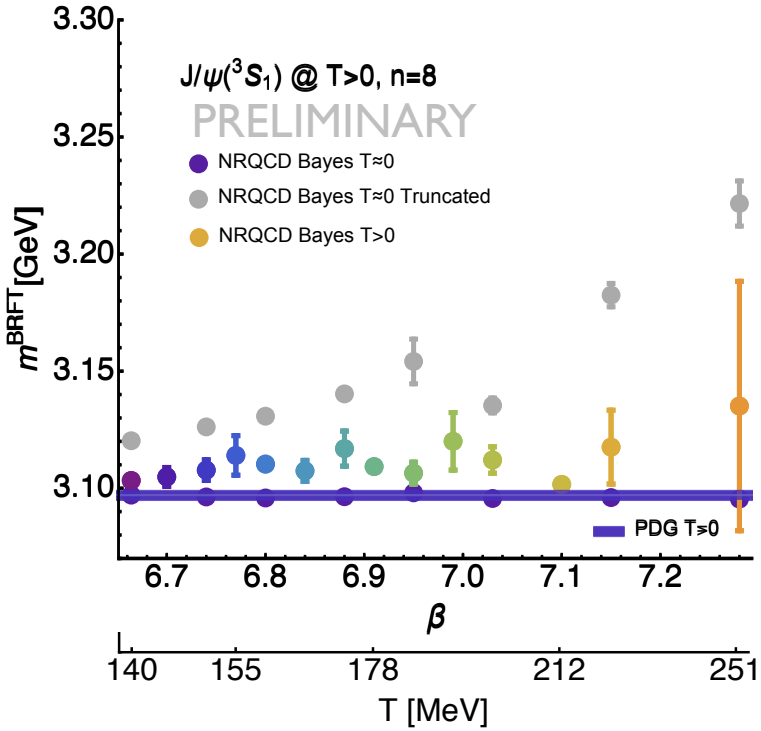




- Naïve inspection of in-medium modification appears to show increasing masses
- BR method systematics: Low number of datapoints introduces shifts to larger masses
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies

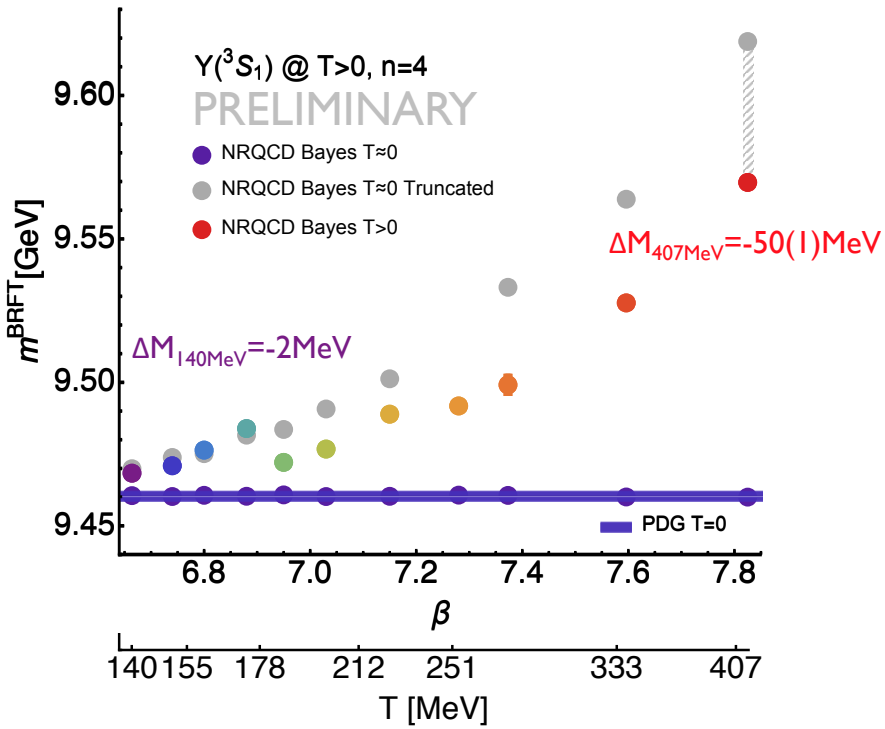
In-medium S-wave mass shifts

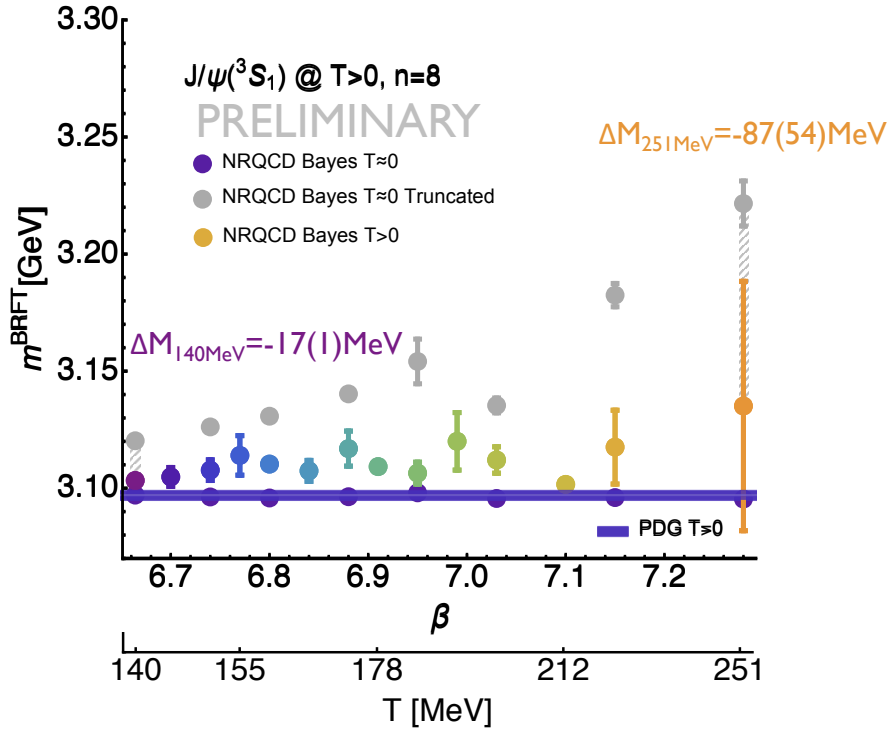




- Naïve inspection of in-medium modification appears to show increasing masses
- BR method systematics: Low number of datapoints introduces shifts to larger masses
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies

In-medium S-wave mass shifts

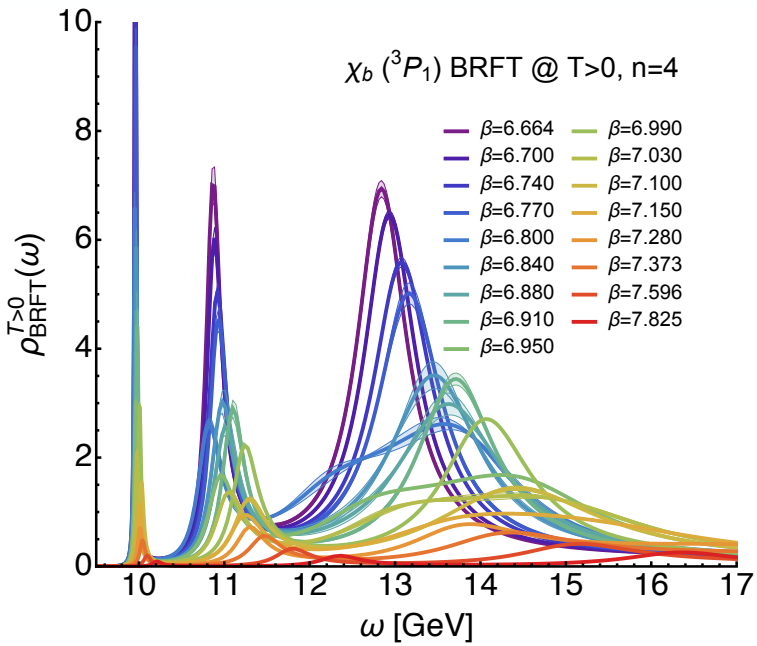


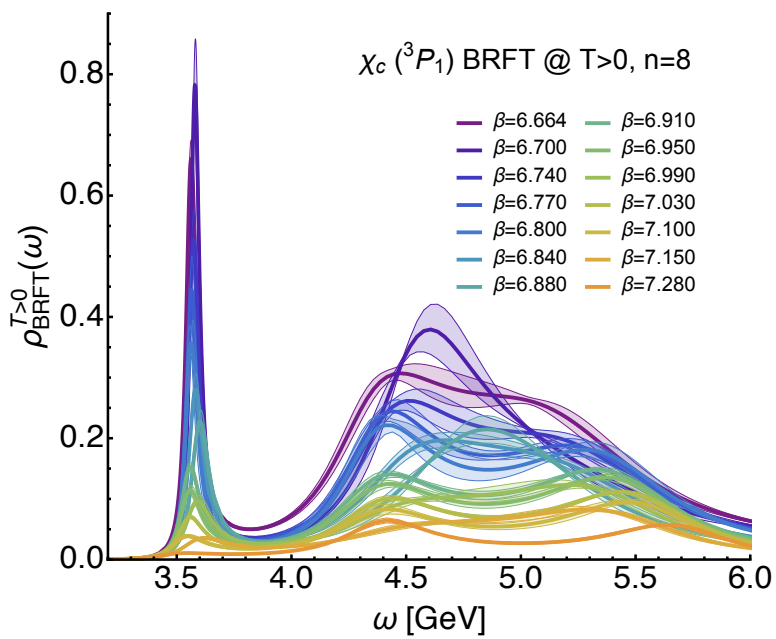


- Naïve inspection of in-medium modification appears to show increasing masses
- BR method systematics: Low number of datapoints introduces shifts to larger masses
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies

NRQCD P-wave spectra at T>0

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

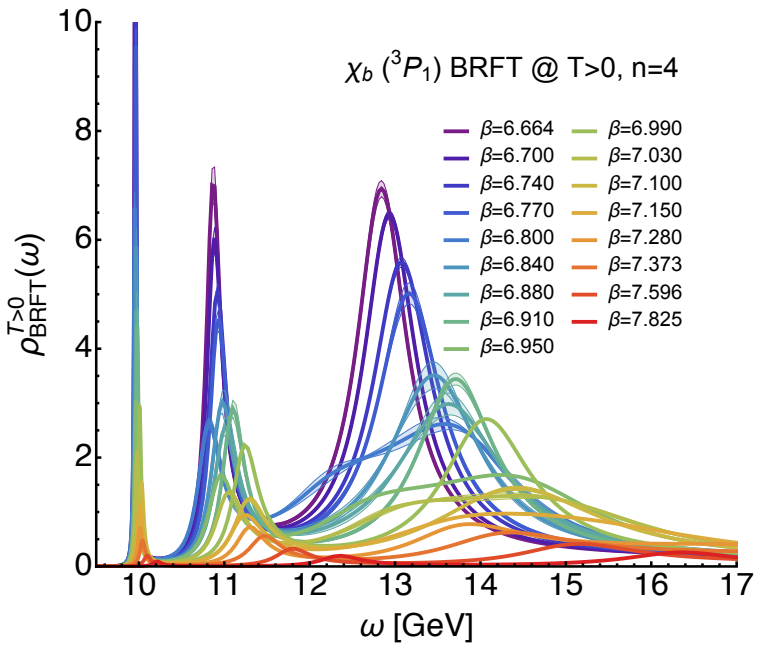


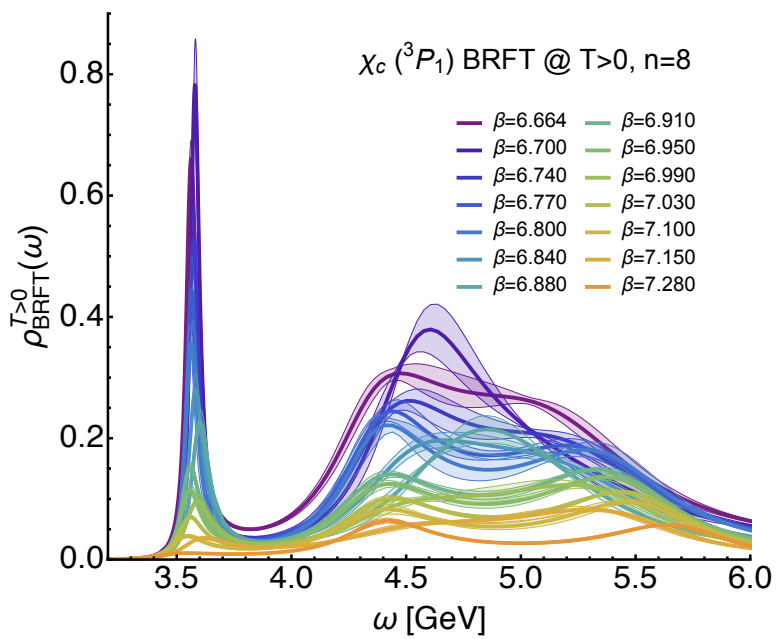


- Lower signal to noise ratio in underlying correlators makes reconstruction less precise

NRQCD P-wave spectra at T>0

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

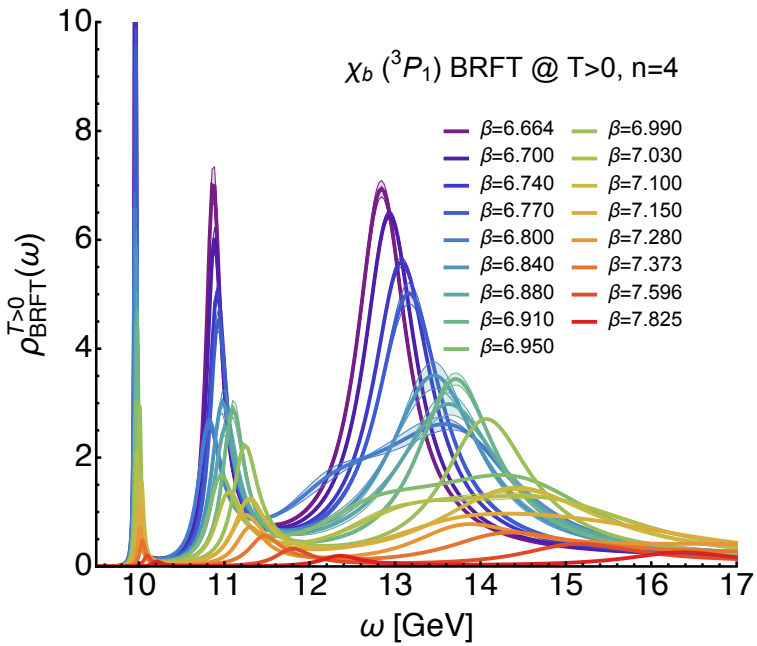


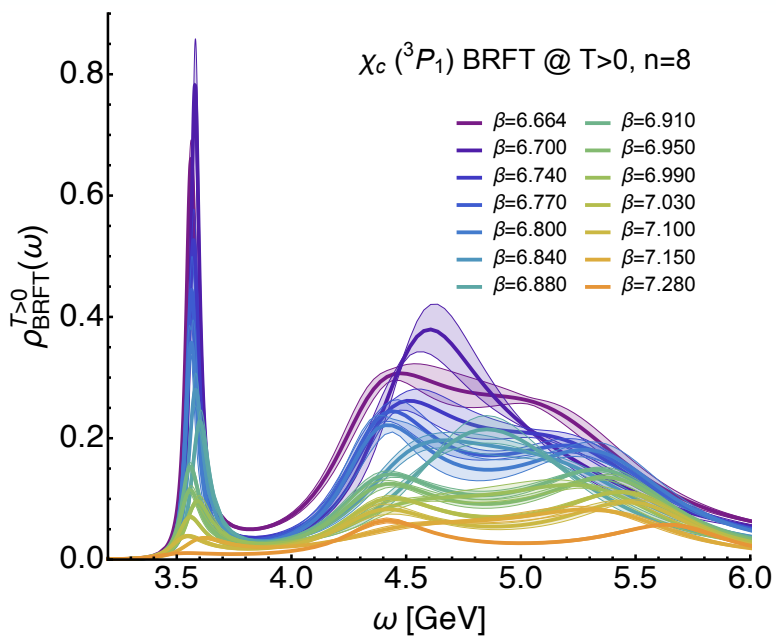


- Lower signal to noise ratio in underlying correlators makes reconstruction less precise
- Ground state well resolved and well separated from higher lying structures

NRQCD P-wave spectra at T>0

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

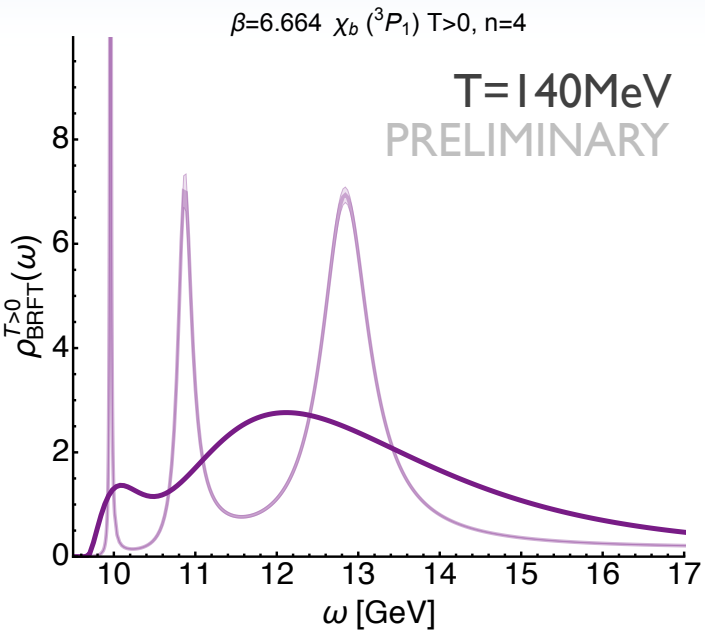


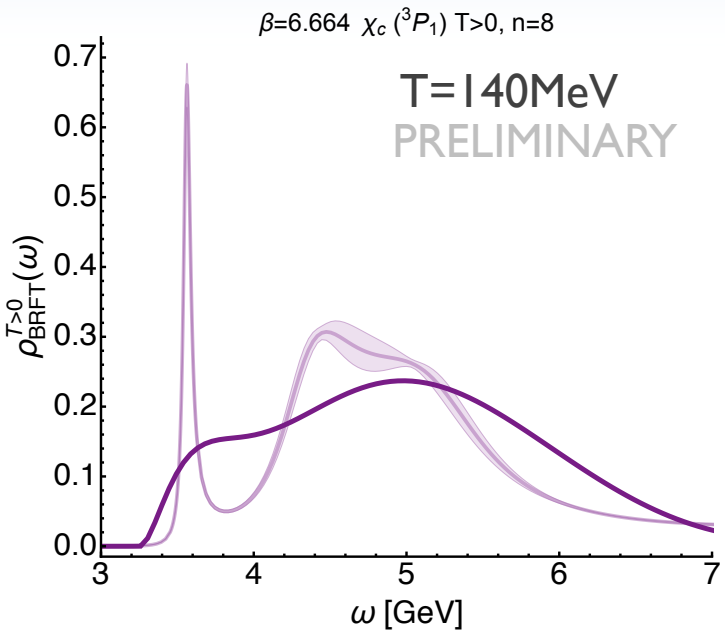


- Lower signal to noise ratio in underlying correlators makes reconstruction less precise
- Ground state well resolved and well separated from higher lying structures
- Gradual broadening and shifting of lowest lying peak visible

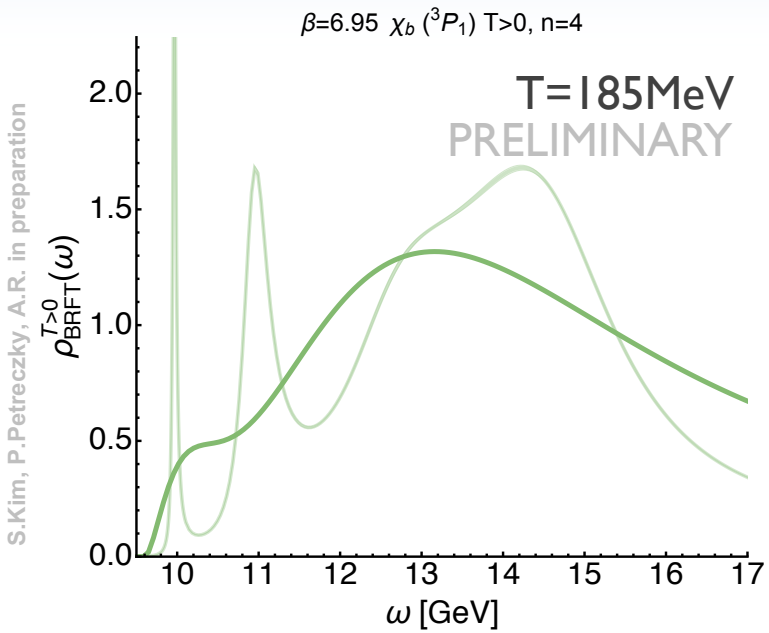
Survival of ground state signals?

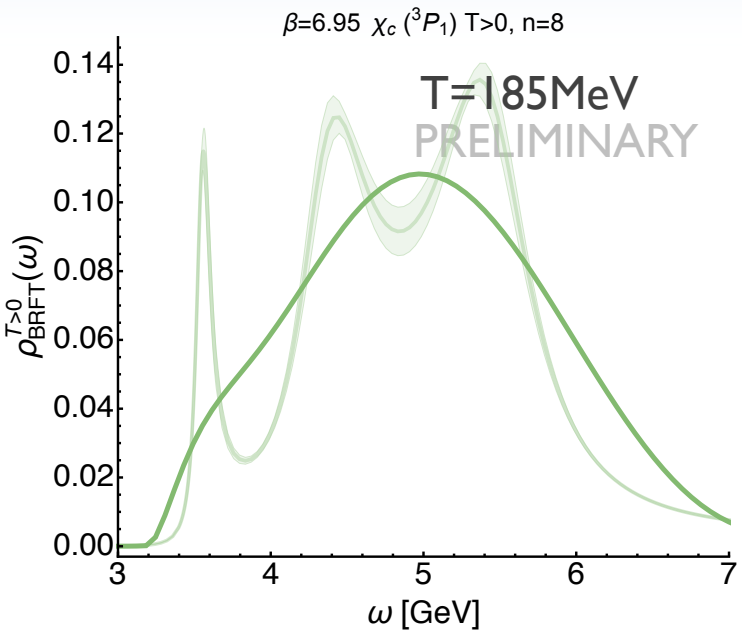
S.Kim, P.Petreczky, A.R. in preparation



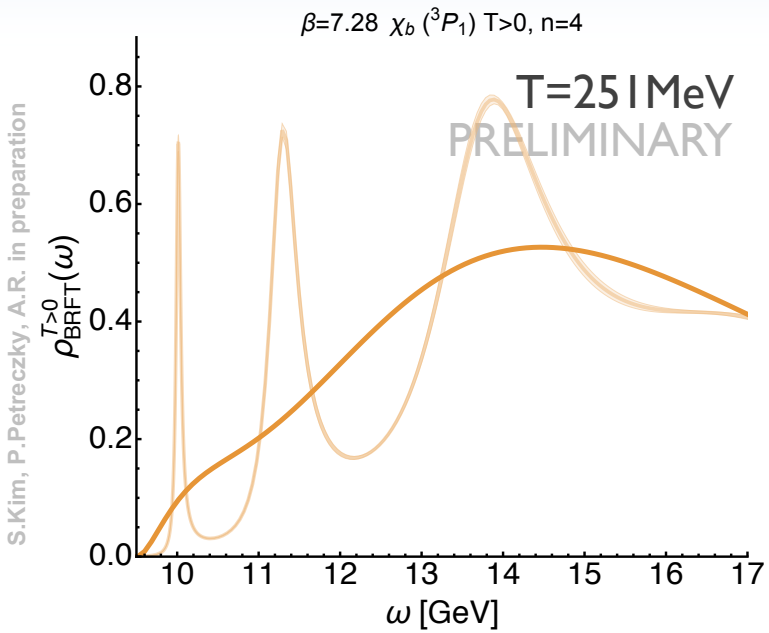


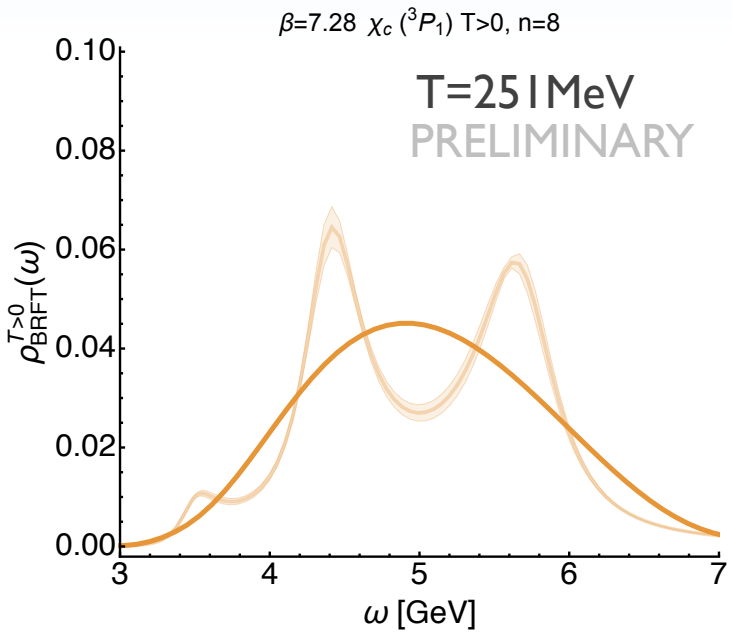
Survival of ground state signals?



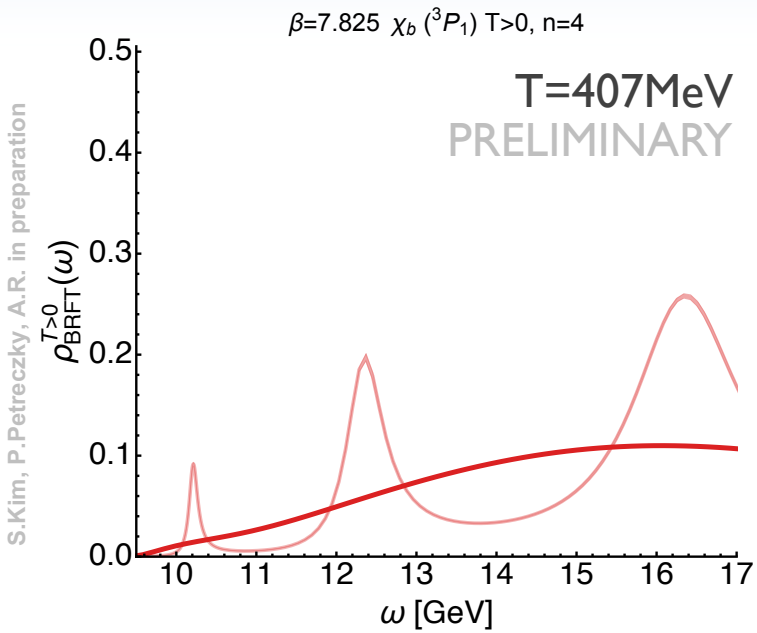


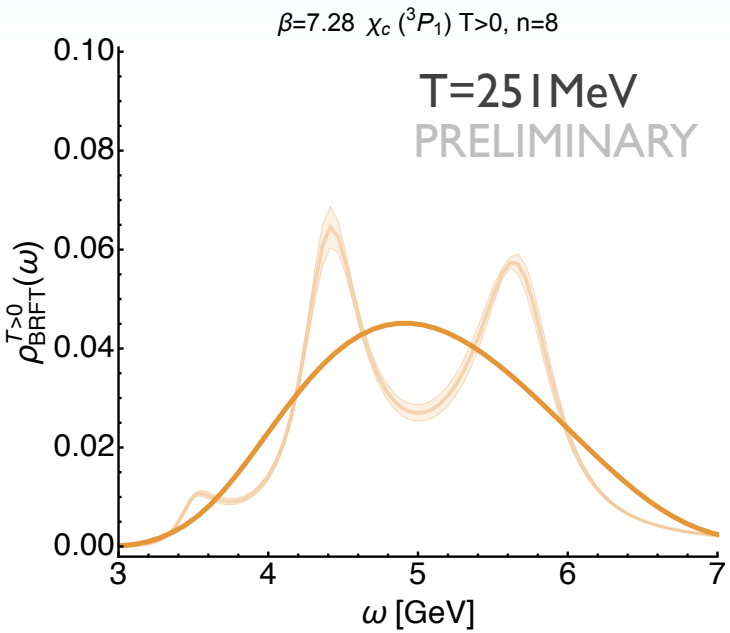
Survival of ground state signals?



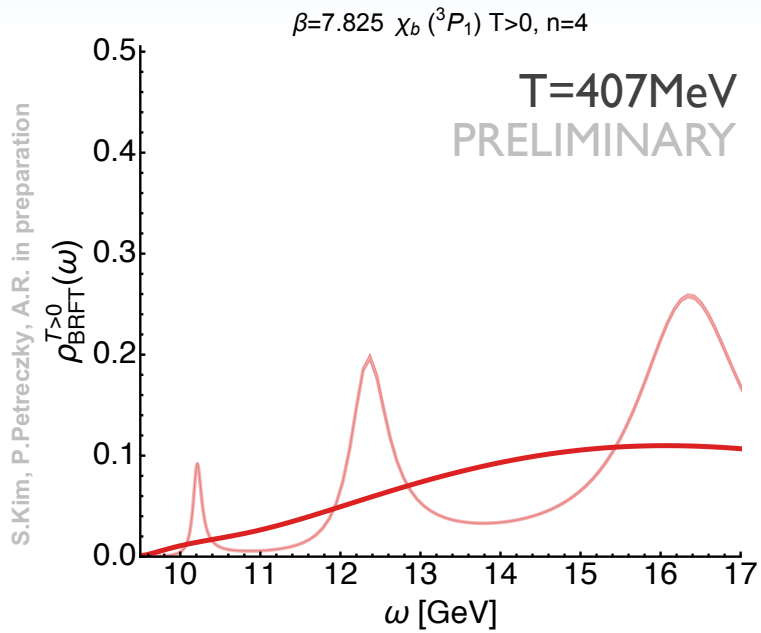


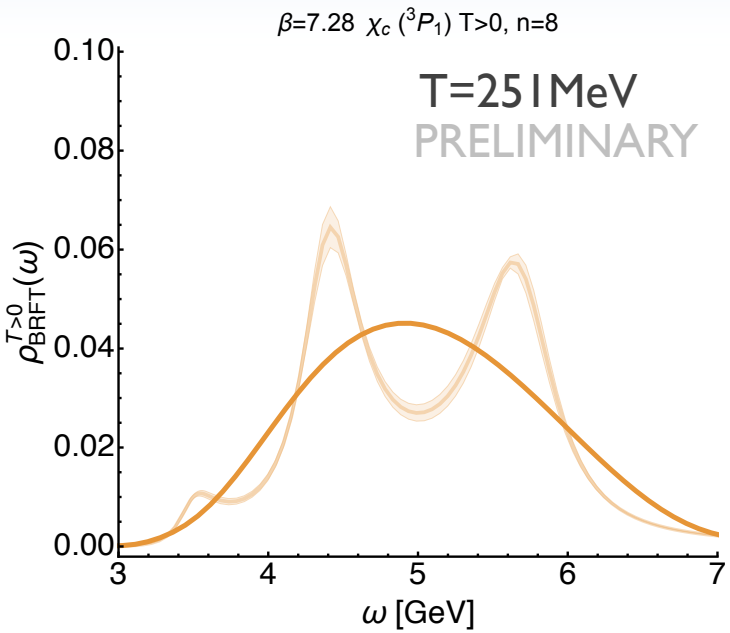
Survival of ground state signals?





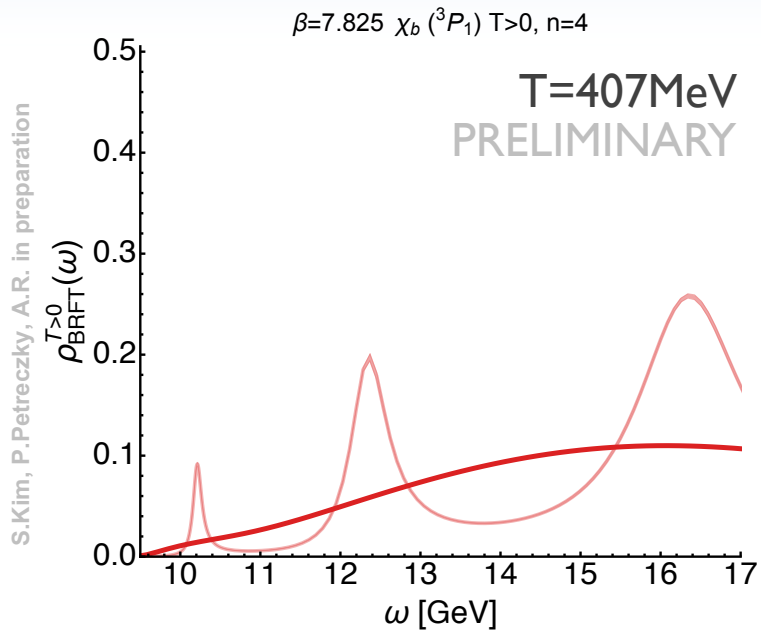
Survival of ground state signals?

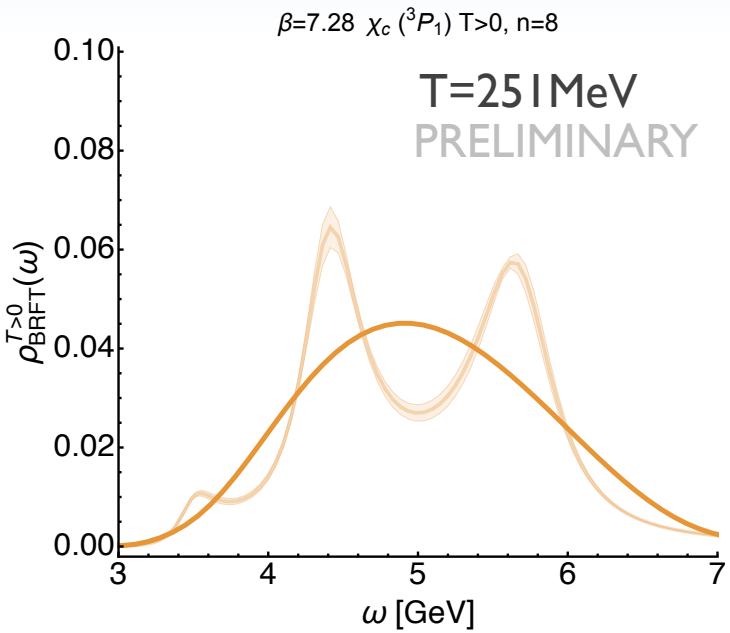




- New “low-gain” BR method shows gradual weakening of ground state signal

Survival of ground state signals?



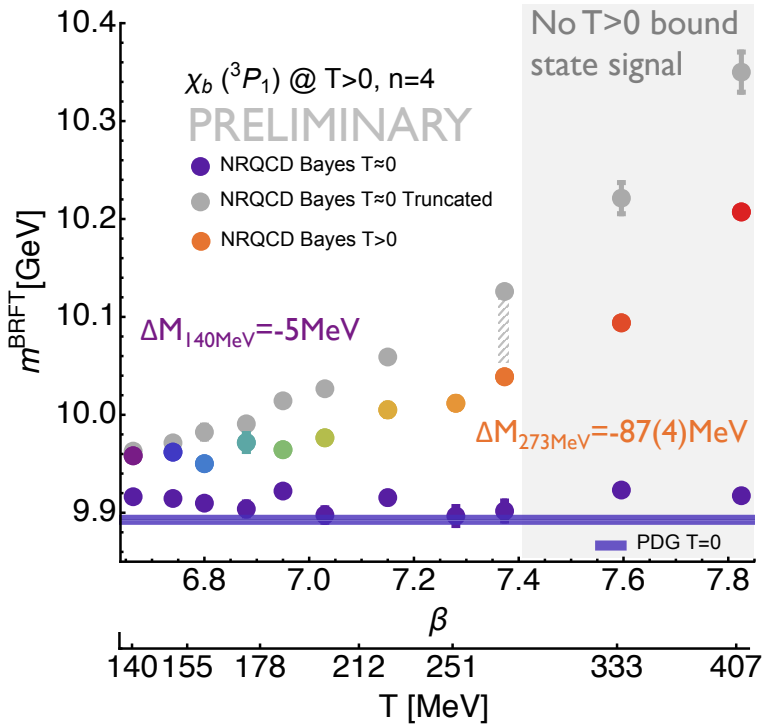


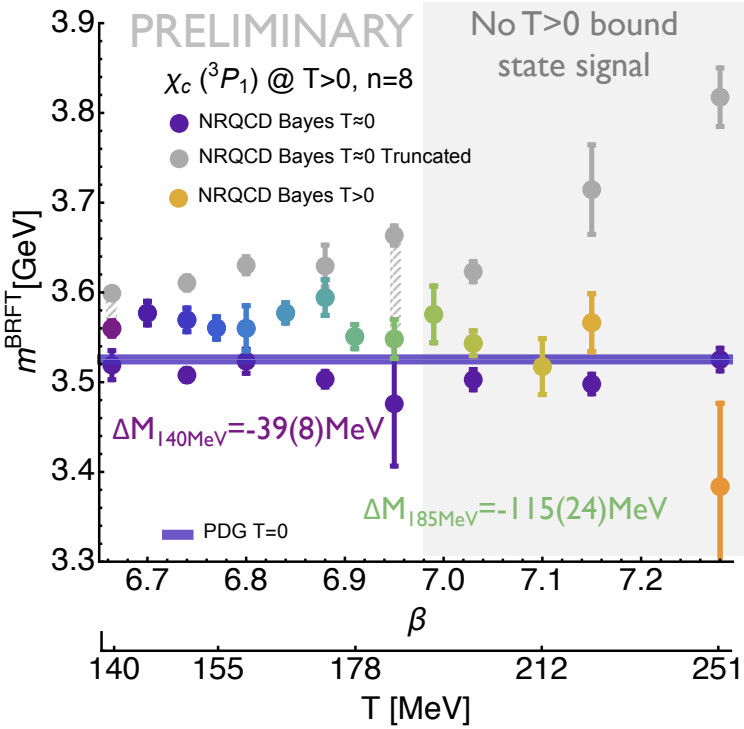
- New "low-gain" BR method shows gradual weakening of ground state signal
- Genuine bound state signal lost at intermediate temperatures

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

How to improve spectral accuracy?

- Intrinsic problem of standard spectral reconstruction: exponential information loss

$$D(\tau) = \int_0^\infty d\omega \, \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh[\omega\beta/2]} \, \rho(\omega)$$

How to improve spectral accuracy?

- Intrinsic problem of standard spectral reconstruction: exponential information loss

$$D(\tau) = \int_0^\infty d\omega \, \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh[\omega\beta/2]} \, \rho(\omega) \qquad D(\mu) = \int_0^\infty d\omega \frac{2\omega}{\mu^2 + \omega^2} \rho(\omega)$$

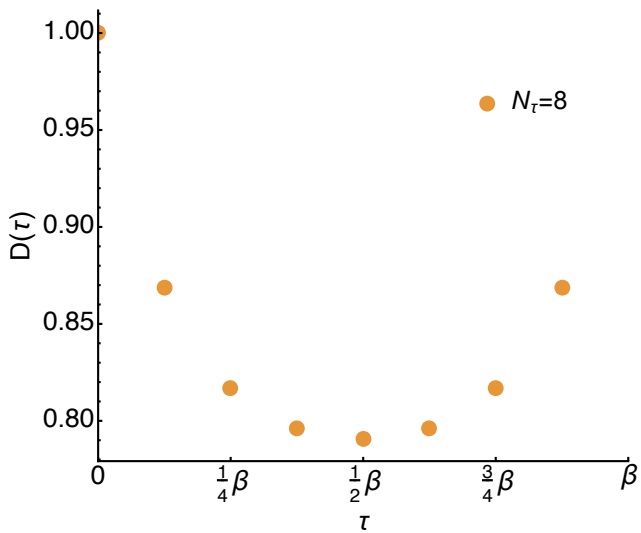
- 1st part of the remedy: go over to imaginary frequencies

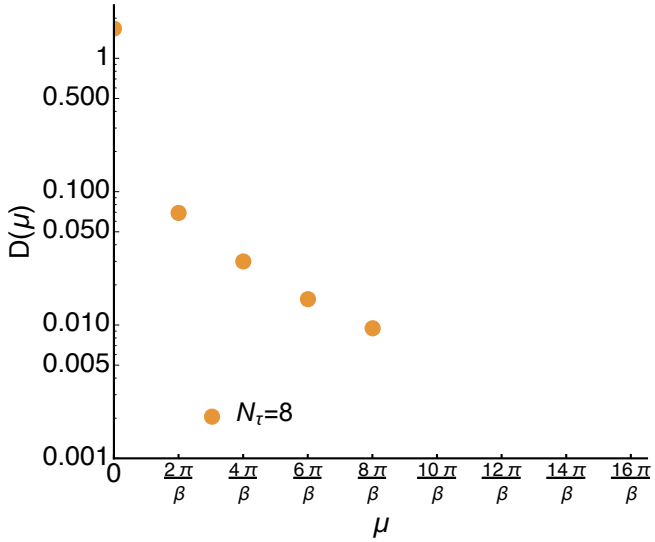
How to improve spectral accuracy?

- Intrinsic problem of standard spectral reconstruction: exponential information loss

$$D(\tau) = \int_0^\infty d\omega \, \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh[\omega\beta/2]} \, \rho(\omega) \qquad D(\mu) = \int_0^\infty d\omega \, \frac{2\omega}{\mu^2 + \omega^2} \rho(\omega)$$

- 1st part of the remedy: go over to imaginary frequencies





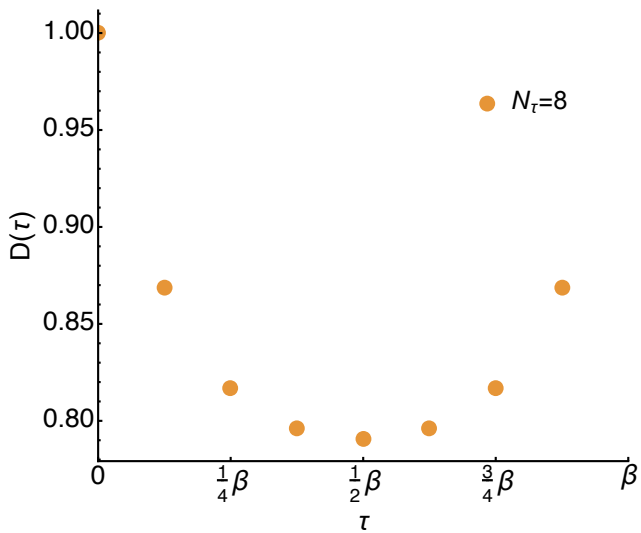
- Standard lattice simulation access only Matsubara frequencies: $\mu = 2\pi n T, \; n \in \mathbb{Z}$

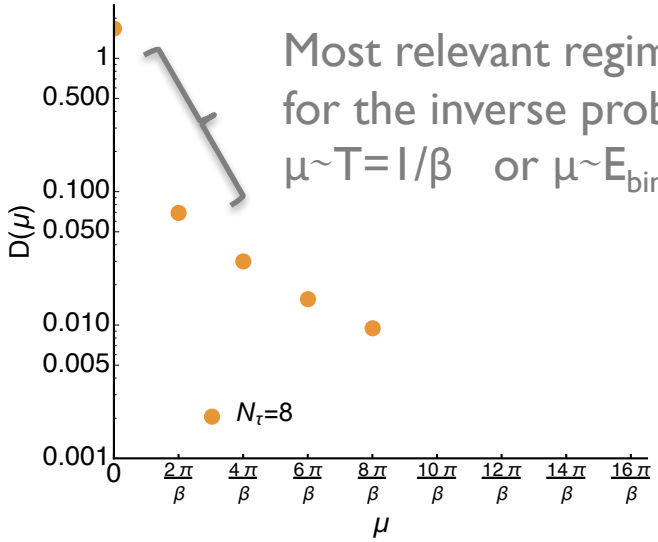
How to improve spectral accuracy?

- Intrinsic problem of standard spectral reconstruction: exponential information loss

$$D(\tau) = \int_0^\infty d\omega \, \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh[\omega\beta/2]} \, \rho(\omega) \qquad D(\mu) = \int_0^\infty d\omega \, \frac{2\omega}{\mu^2 + \omega^2} \rho(\omega)$$

- 1st part of the remedy: go over to imaginary frequencies





Most relevant regime for the inverse problem: $\mu \sim T = 1/\beta$ or $\mu \sim E_{bind}$

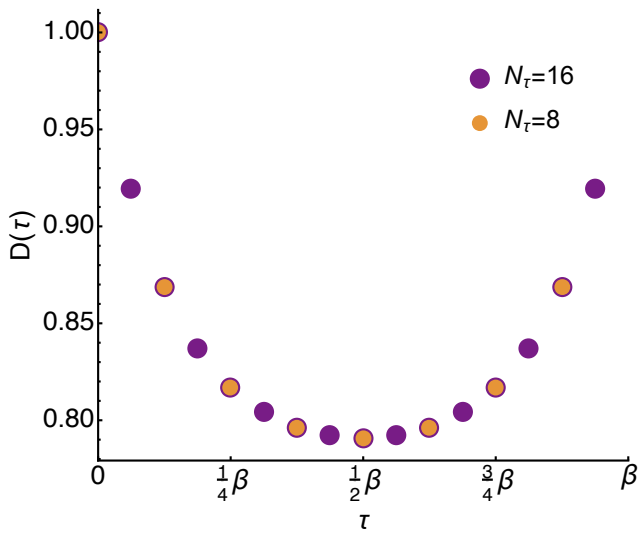
- Standard lattice simulation access only Matsubara frequencies: $\mu = 2\pi n T, \; n \in \mathbb{Z}$

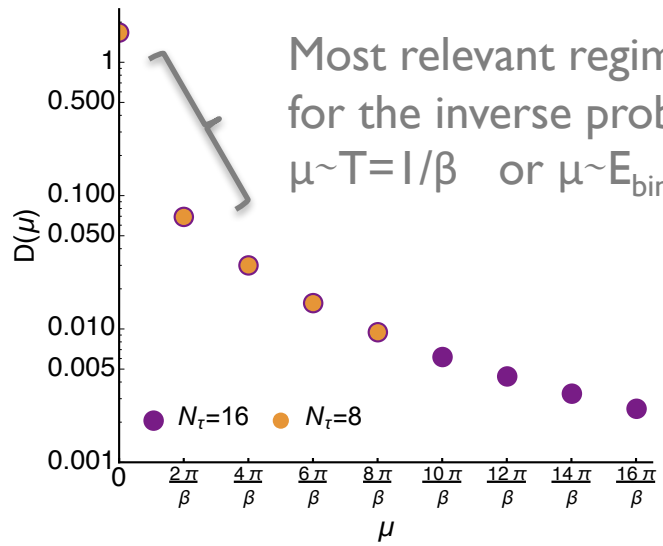
How to improve spectral accuracy?

- Intrinsic problem of standard spectral reconstruction: exponential information loss

$$D(\tau) = \int_0^\infty d\omega \, \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh[\omega\beta/2]} \, \rho(\omega) \qquad D(\mu) = \int_0^\infty d\omega \, \frac{2\omega}{\mu^2 + \omega^2} \rho(\omega)$$

- 1st part of the remedy: go over to imaginary frequencies





Most relevant regime for the inverse problem: $\mu \sim T = 1/\beta$ or $\mu \sim E_{bind}$

- Standard lattice simulation access only Matsubara frequencies: $\mu = 2\pi n T, \; n \in \mathbb{Z}$

A new simulation approach

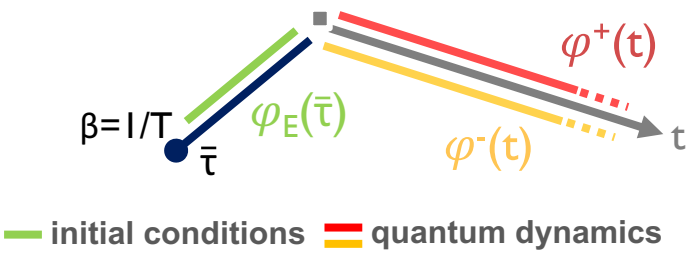
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R.
arXiv:1610.09531

$\bar{\tau}_0 = t_0$



A new simulation approach

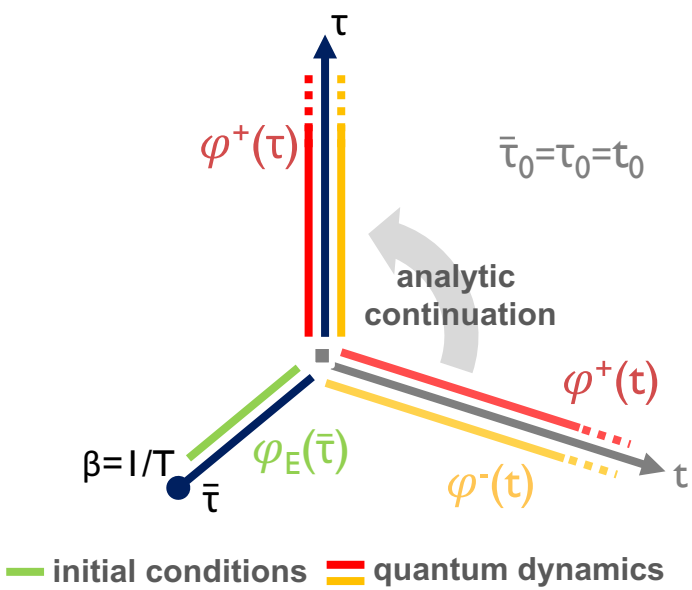
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R.
arXiv:1610.09531

- Rotate real-time contour into an additional *non-compact* Euclidean time ($\varphi^+(\tau=0)=\varphi^+(\tau'=0)$)



A new simulation approach

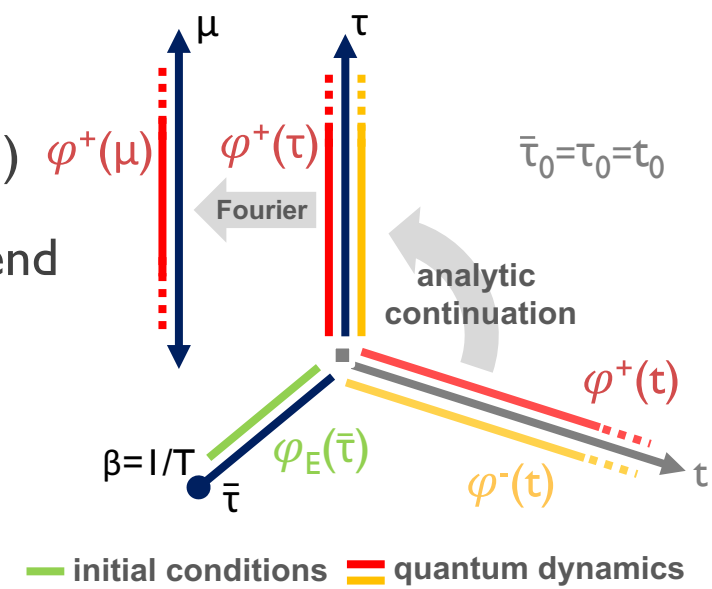
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R. arXiv:1610.09531

- Rotate real-time contour into an additional *non-compact* Euclidean time ($\varphi^+(\tau=0)=\varphi^+(\tau'=0)$)
- To decouple forward and backward branch, extend $\tau' \to \infty$. Then Fourier transform $\tau' \to \mu$.



A new simulation approach

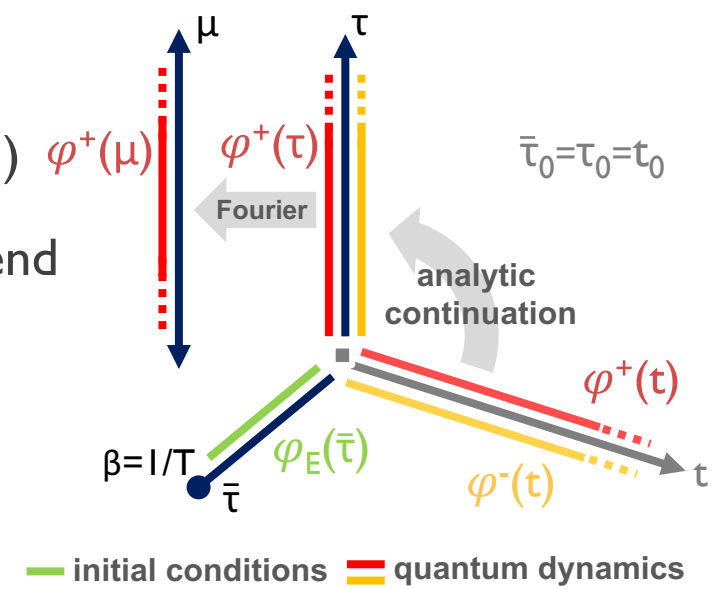
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R. arXiv:1610.09531

- Rotate real-time contour into an additional *non-compact* Euclidean time ($\varphi^+(\tau=0)=\varphi^+(\tau'=0)$)
- To decouple forward and backward branch, extend $\tau' \to \infty$. Then Fourier transform $\tau' \to \mu$.
- Discretize the imaginary frequency domain with higher resolution $N_\mu >> N_\tau$.



A new simulation approach

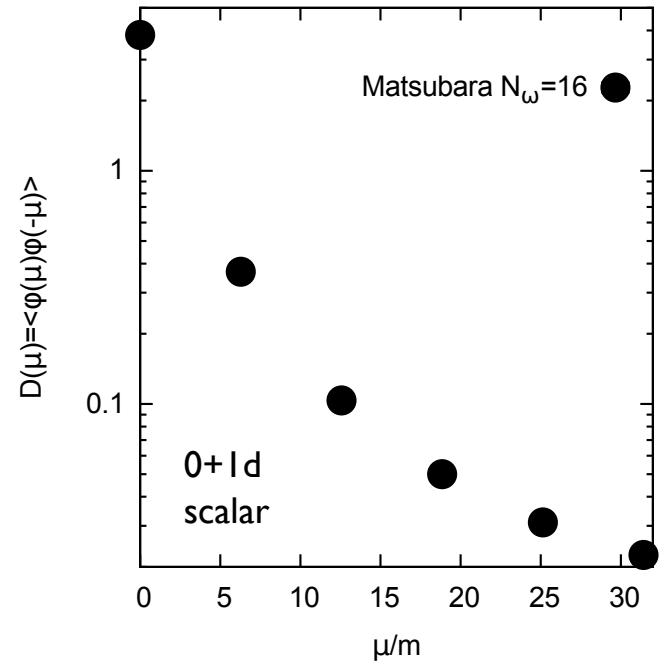
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R.
arXiv:1610.09531

- Rotate real-time contour into an additional *non-compact* Euclidean time ($\varphi^+(\tau=0)=\varphi^+(\tau'=0)$)
- To decouple forward and backward branch, extend $\tau' \to \infty$. Then Fourier transform $\tau' \to \mu$.
- Discretize the imaginary frequency domain with higher resolution $N_\mu >> N_\tau$.



A new simulation approach

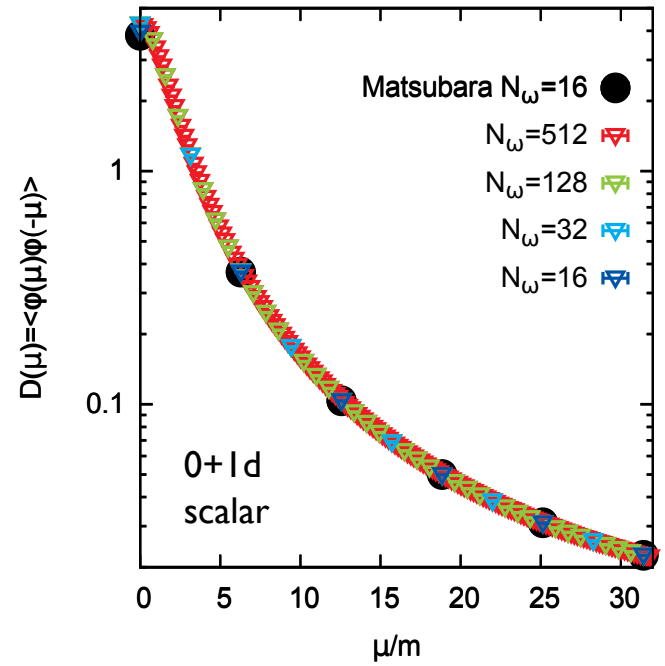
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R.
arXiv:1610.09531

- Rotate real-time contour into an additional *non-compact* Euclidean time ($\varphi^+(\tau=0)=\varphi^+(\tau'=0)$)
- To decouple forward and backward branch, extend $\tau' \to \infty$. Then Fourier transform $\tau' \to \mu$.
- Discretize the imaginary frequency domain with higher resolution $N_\mu >> N_\tau$.



A new simulation approach

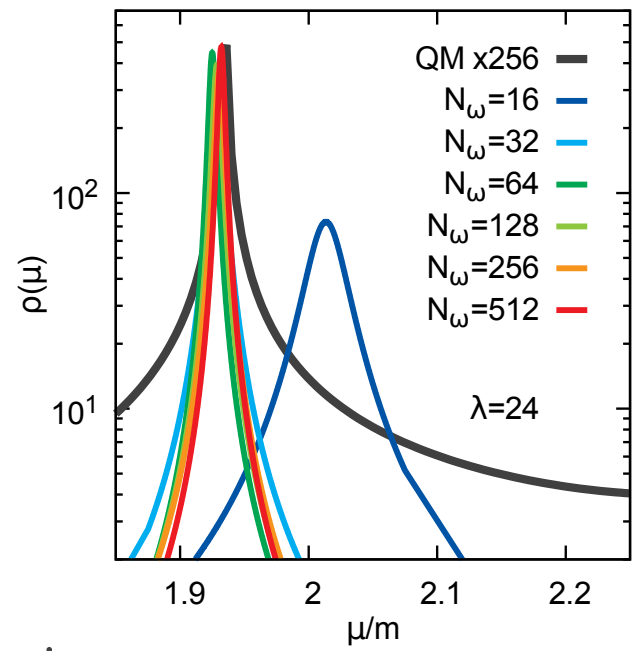
- How can we overcome this limitation? Simulate directly in imaginary frequency.

$$\mathcal{Z} = \underbrace{\int [d\varphi_0^+][d\varphi_0^-]\langle\varphi_0^+|e^{-\beta\hat{H}}|\varphi_0^-\rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

- Only in thermal equilibrium: ρ depends solely on φ^+ correlations

J. Pawlowski and A.R.
arXiv:1610.09531

- Rotate real-time contour into an additional *non-compact* Euclidean time ($\varphi^+(\tau=0)=\varphi^+(\tau'=0)$)
- To decouple forward and backward branch, extend $\tau' \to \infty$. Then Fourier transform $\tau' \to \mu$.
- Discretize the imaginary frequency domain with higher resolution $N_\mu >> N_\tau$.



- 0+1d scalar: significantly improved spectral reconstructions

Conclusions

- Recently: intuition & observables (ψ'/J/ψ) from lattice QCD potential studies
  Y.Burnier, O.Kaczmarek, A.R. JHEP 1512 (2015) 101, JHEP 1610 (2016) 032
- Need to validate the results from a genuine field theory: lattice NRQCD
  S.Kim, P. Petreczky, A.R.: Phys.Rev. D91 (2015) 54511, Nucl.Phys. A956 (2016) 713 and work in progress
  - **Progress I:** HotQCD lattices provide higher statistics and larger temperature range
  - **Progress II:** Improved Bayesian spectral reconstruction reduces methods uncertainties
  - **Progress III:** Extension of the 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**
  - **S-wave:** Υ(1S) up to T=407MeV (ΔM=-50MeV) J/ψ(1S) up to T=251MeV (ΔM=-87MeV)
  - **P-wave:** χ_b(1P) up to T=273MeV (ΔM=-87MeV) χ_c(1P) up to T=185MeV (ΔM=-115MeV)
- Future plans: Improve spectral reconstruction by simulating in imaginary freqs
  J. Pawlowski and A.R. arXiv:1610.09531

Conclusions

- Recently: intuition & observables (ψ'/J/ψ) from lattice QCD potential studies
  Y.Burnier, O.Kaczmarek, A.R. JHEP 1512 (2015) 101, JHEP 1610 (2016) 032
- Need to validate the results from a genuine field theory: lattice NRQCD
  S.Kim, P. Petreczky, A.R.: Phys.Rev. D91 (2015) 54511, Nucl.Phys. A956 (2016) 713 and work in progress
  - **Progress I:** HotQCD lattices provide higher statistics and larger temperature range
  - **Progress II:** Improved Bayesian spectral reconstruction reduces methods uncertainties
  - **Progress III:** Extension of the 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**
  - **S-wave:** Υ(1S) up to T=407MeV (ΔM=-50MeV) J/ψ(1S) up to T=251MeV (ΔM=-87MeV)
  - **P-wave:** χ_b(1P) up to T=273MeV (ΔM=-87MeV) χ_c(1P) up to T=185MeV (ΔM=-115MeV)
- Future plans: Improve spectral reconstruction by simulating in imaginary freqs
  J. Pawlowski and A.R. arXiv:1610.09531

Thank you for your attention