In-medium quarkonium properties from a lattice QCD based effective field theory

Alexander Rothkopf
Institute for Theoretical Physics
Heidelberg University

in collaboration with S.Kim and P. Petreczky

References:

Y. Burnier, A.R.: Phys.Rev.Lett. 111 (2013) 182003
S.Kim, P. Petreczky, A.R.: Phys.Rev. D 91 (2015) 054511
and work in progress

THE XXVTH INT. CONFERENCE ON ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS – KOBE, JAPAN – SEPTEMBER 29TH 2015

Motivation: Heavy-Ion Collisions

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

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

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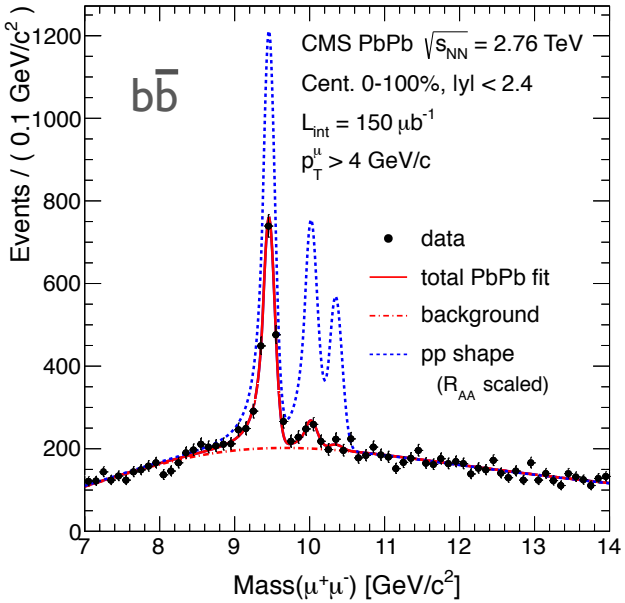
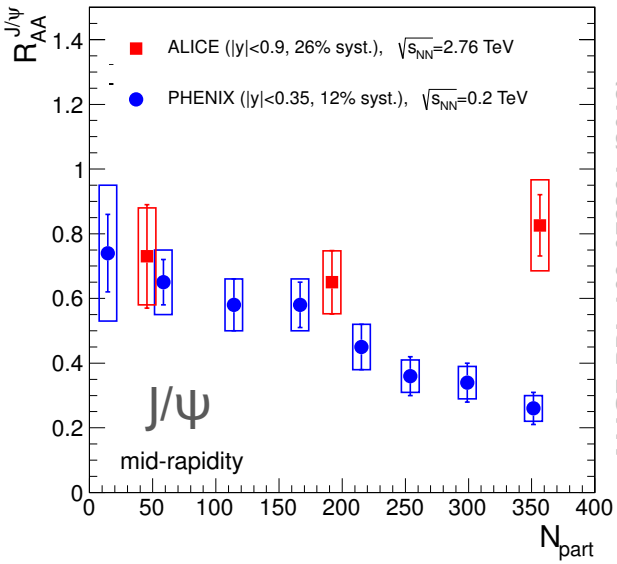


CMS, PRL 109 222301 (2012)



ALICE, PRL 109, 072301 (2012)
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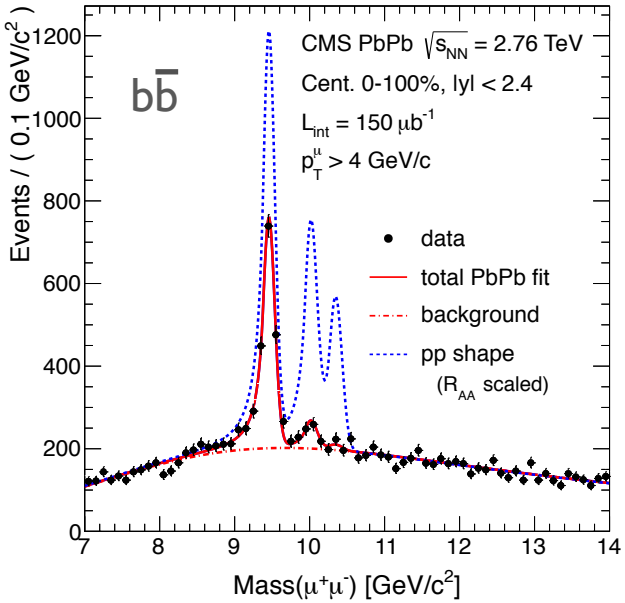

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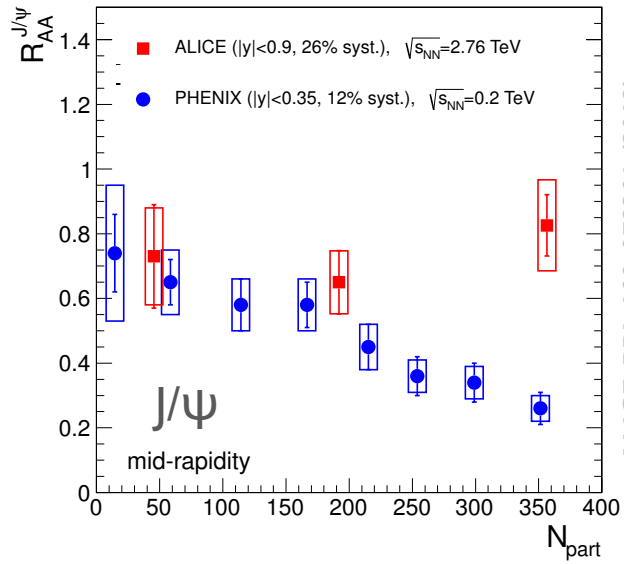

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- Theory goal: 1st principles insight into in-medium $Q\bar{Q}$ in heavy-ion collisions

Two limits for in-medium $Q\bar{Q}$

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

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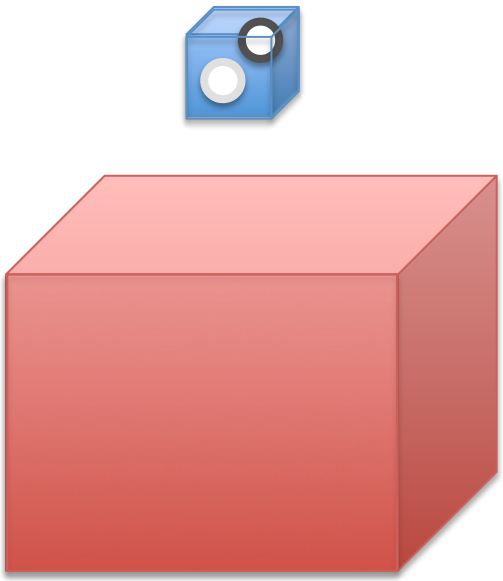

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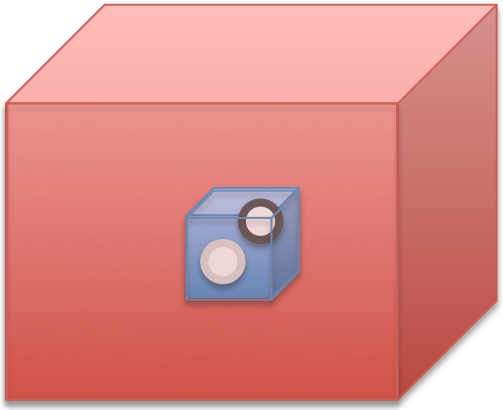

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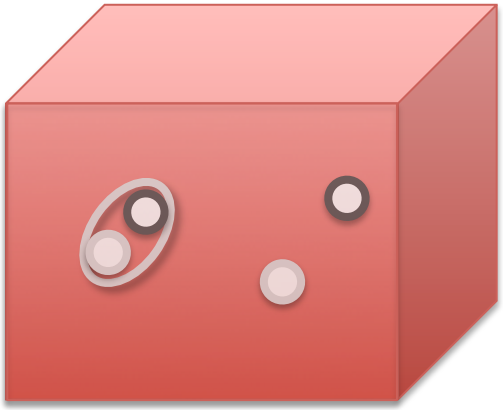

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modern approach: LATTICE QCD meson spectra

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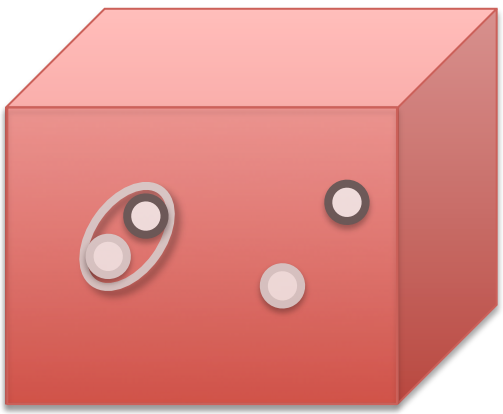

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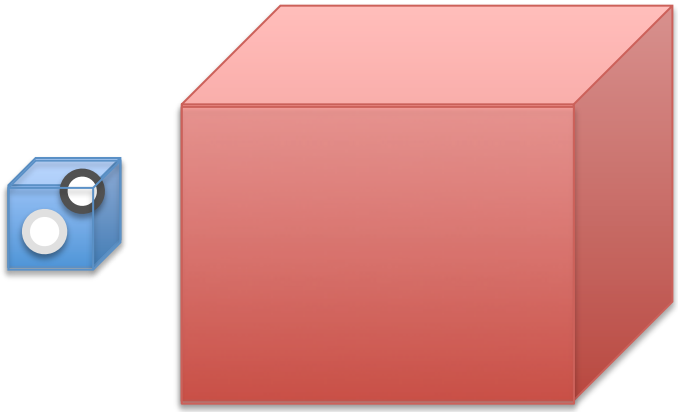

Quarkonium as Open-Quantum System
see e.g. Y. Akamatsu, A.R. PRD85 (2012) 105011

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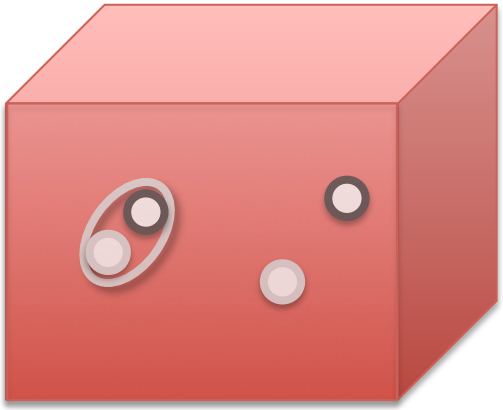

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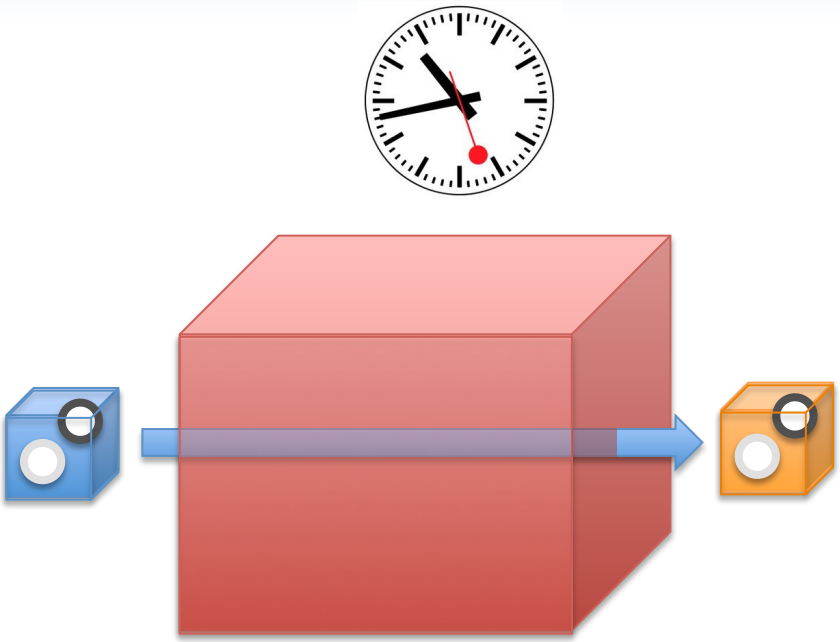

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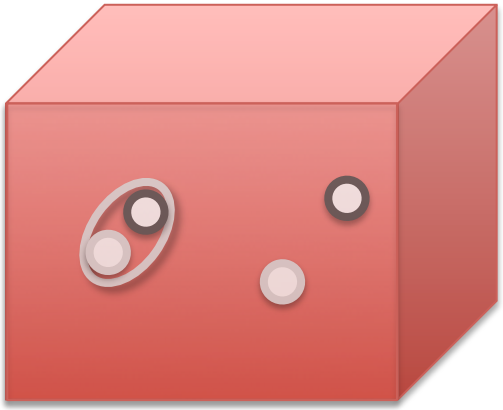

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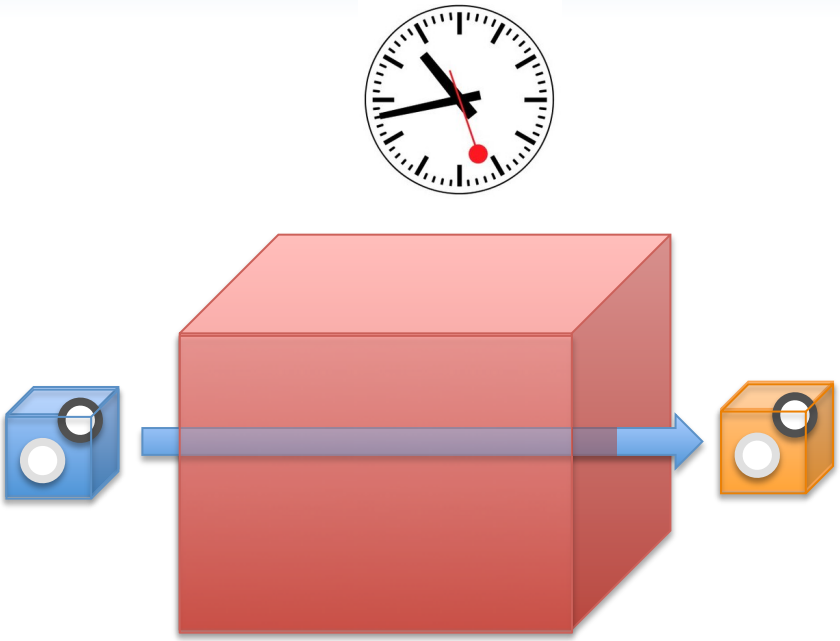

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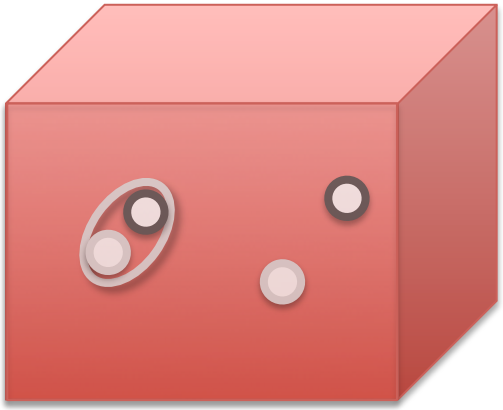

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Heavy quarks on the lattice

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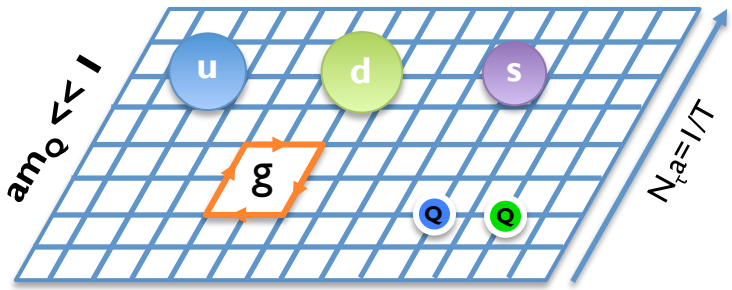
Relativistic treatment of light and heavy d.o.f.



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

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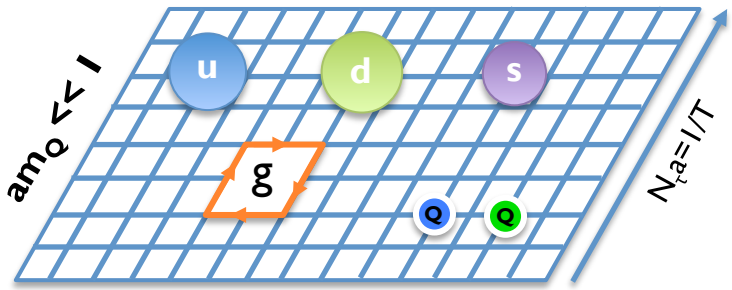

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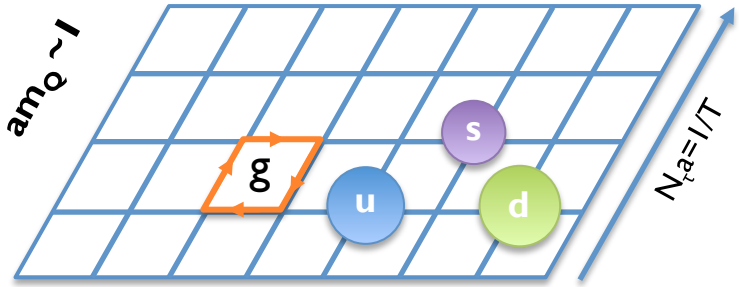
$$\frac{\Lambda_{QCD}}{m_Q} \ll 1$$

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



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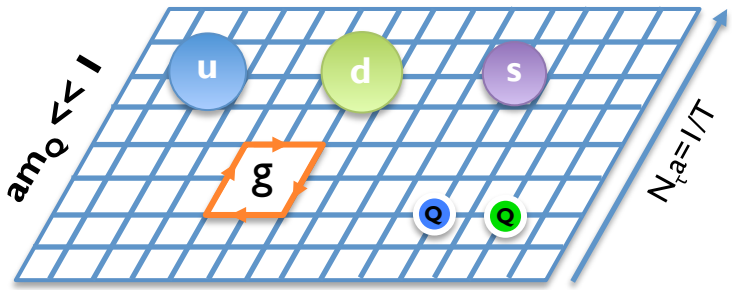

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Kin. eq. non-relativistic $Q\bar{Q}$ in a background of light medium d.o.f.

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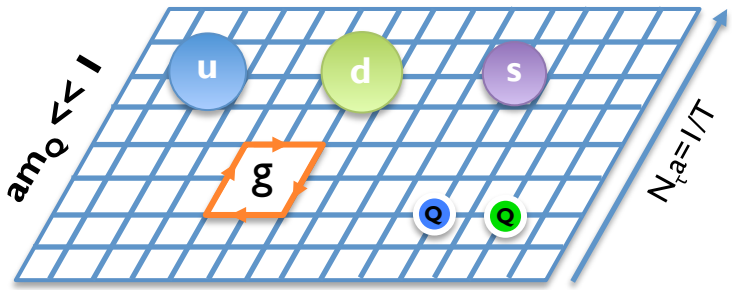

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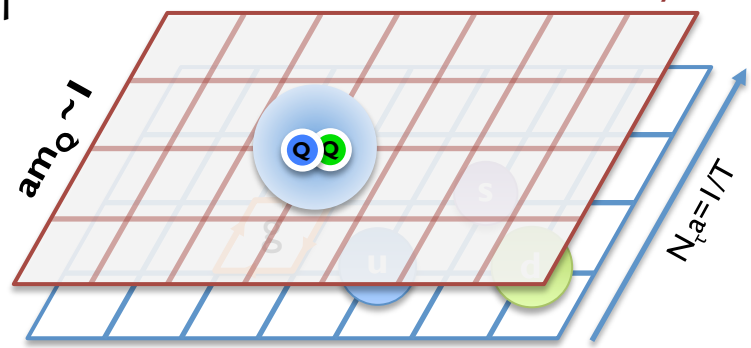
$Q\bar{Q}$ in NRQCD effective theory



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 $1/m_Q a$, includes $v \neq 0$ contributions
    Thacker, Lepage Phys.Rev. D43 (1991) 196-208
  - scale setting requires exp. input - -> successful in ab-initio predictions e.g. $m(\eta_b(2S))$
    Dowdall et. al., PRD85, 054509 (2012)

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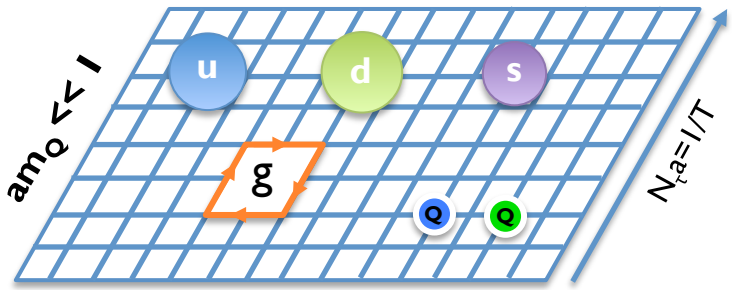

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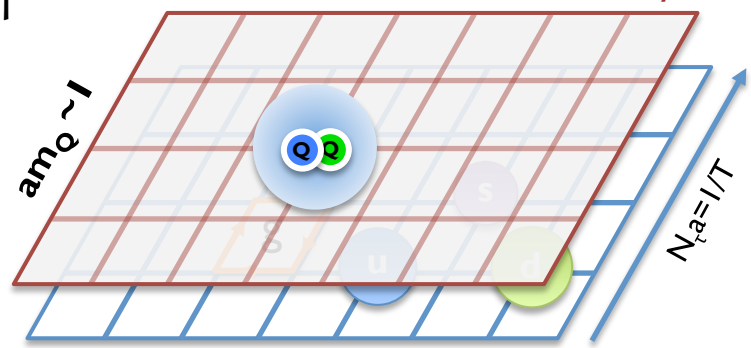

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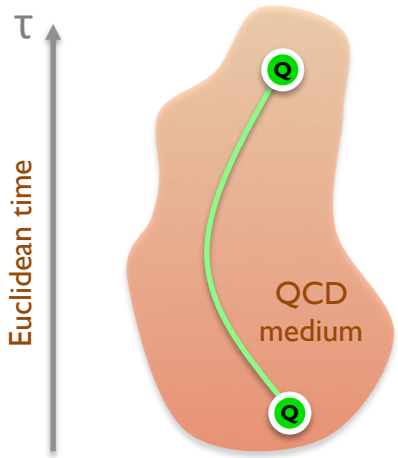
- Recent **progress**: realistic simulations of the QCD medium by the HotQCD collab.
  HotQCD PRD85 (2012) 054503, PRD90 (2014) 094503
  - m_π=161MeV T= [140 – 249] MeV $m_b a$= [2.759 – 1.559] $m_c a$= [0.757 – 0.427]

Correlation functions in NRQCD



Non-rel. propagator of
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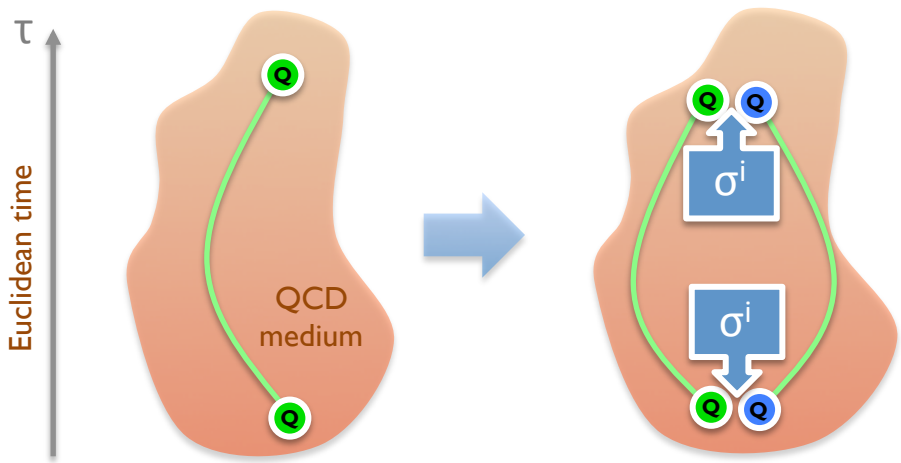

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QQ propagator projected to a certain channel

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

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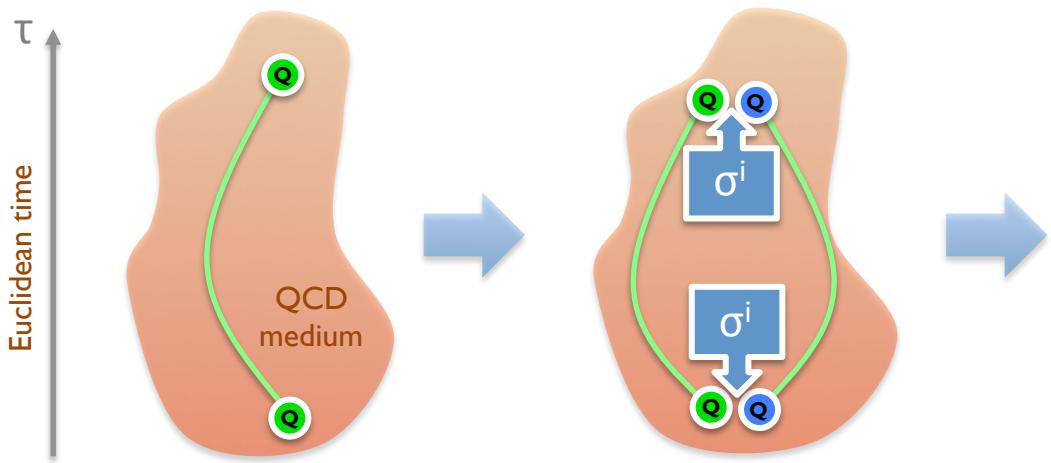

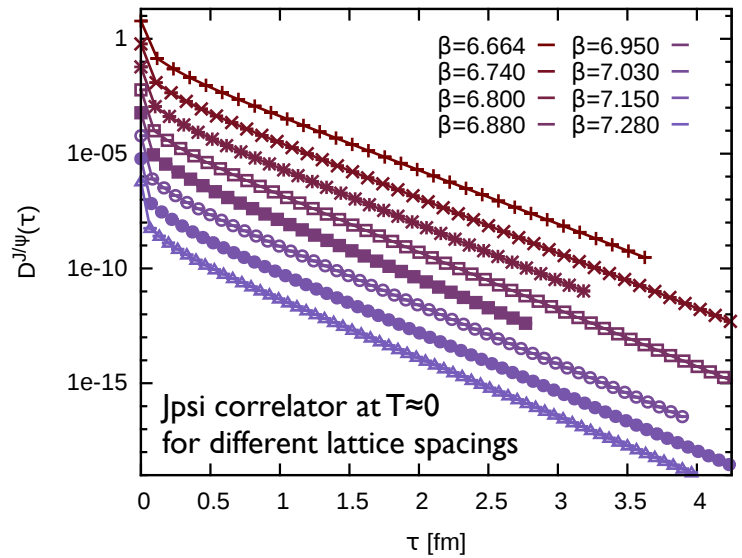

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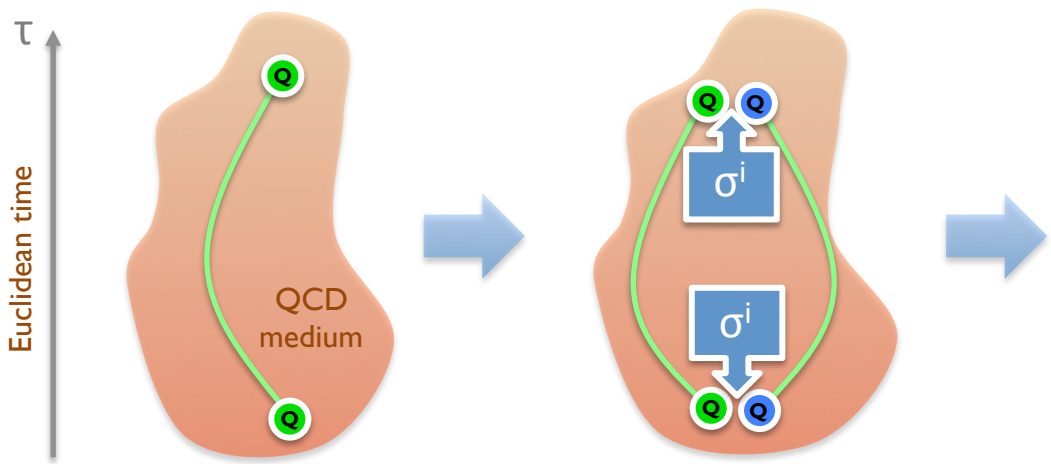

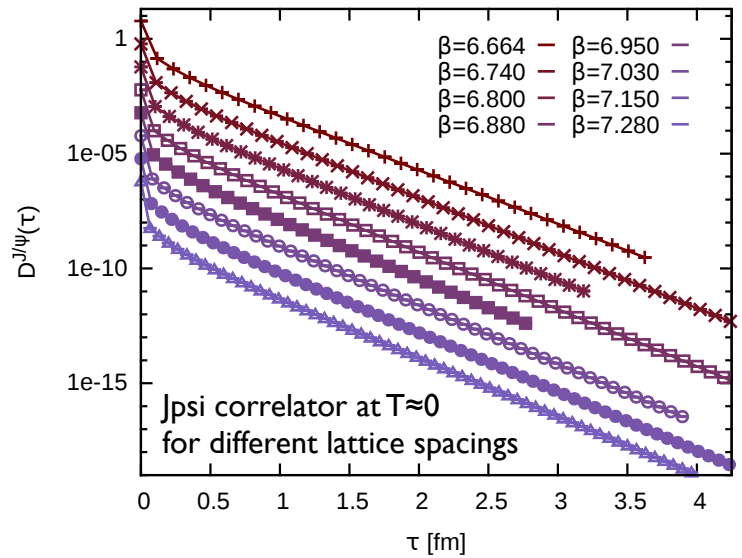

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Ratio of T>0 and T≈0 correlators: estimate of overall in-medium effects

Bayesian spectra in lattice NRQCD

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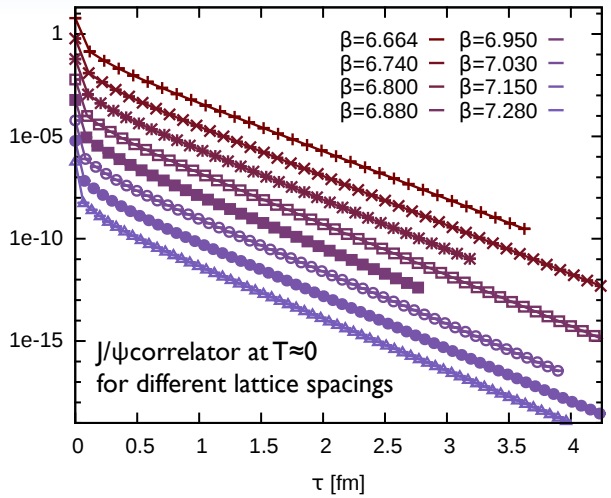
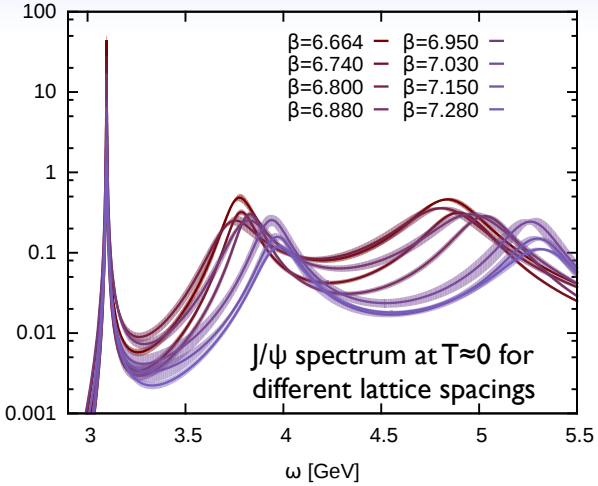


$$D(\tau) = \int_{-2M_Q}^{\infty} d\omega e^{-\tau\omega} \rho(\omega)$$



- Inversion of Laplace transform required to obtain spectra: Inherently Ill-defined

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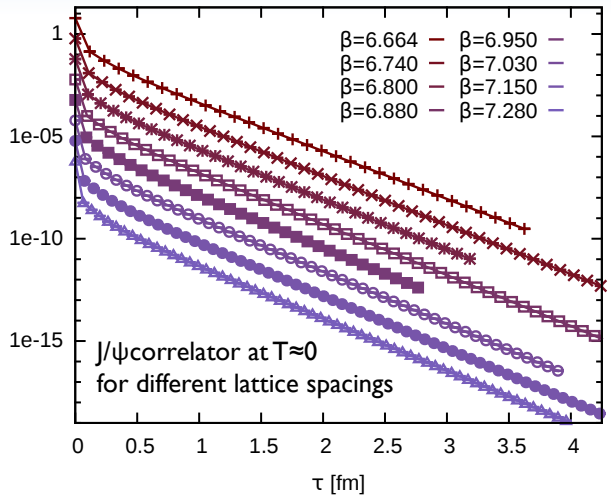
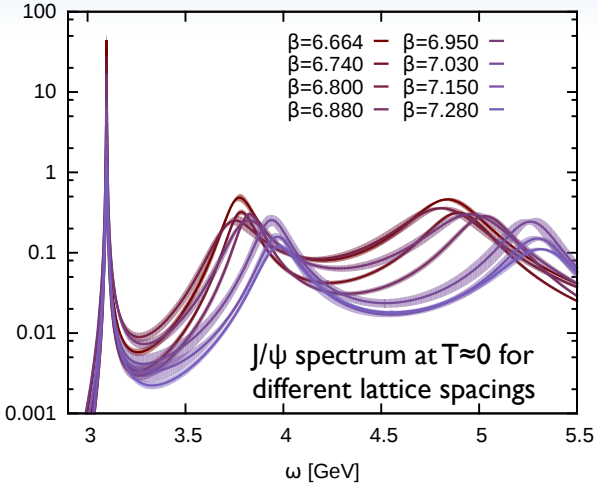


$$D_i = \sum_{l=1}^{N_\omega} \exp[-\omega_l \tau_i]\, \rho_l\, \Delta\omega_l$$

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



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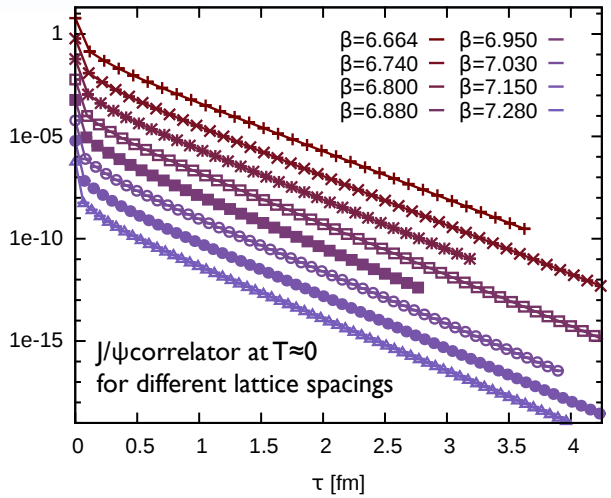

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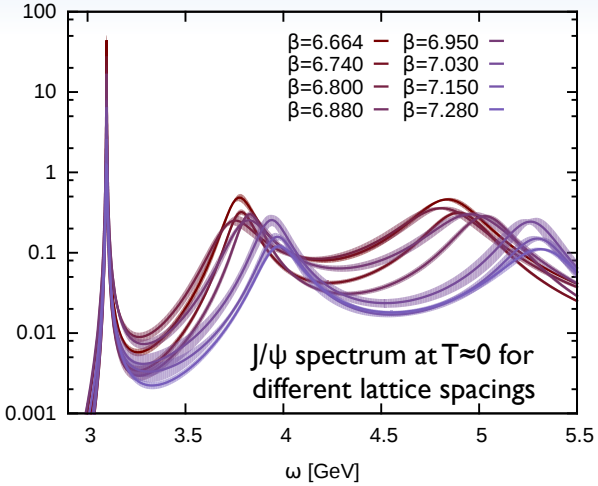

- Inversion of Laplace transform required to obtain spectra: Inherently Ill-defined
- Give meaning to problem by incorporating prior knowledge: Bayesian approach
  - Bayes theorem: Regularize the naïve χ^2 functional P[D|ρ] through a prior P[ρ|I]

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

Asakawa, Hatsuda, Nakahara,
Prog.Part.Nucl.Phys. 46 (2001) 459

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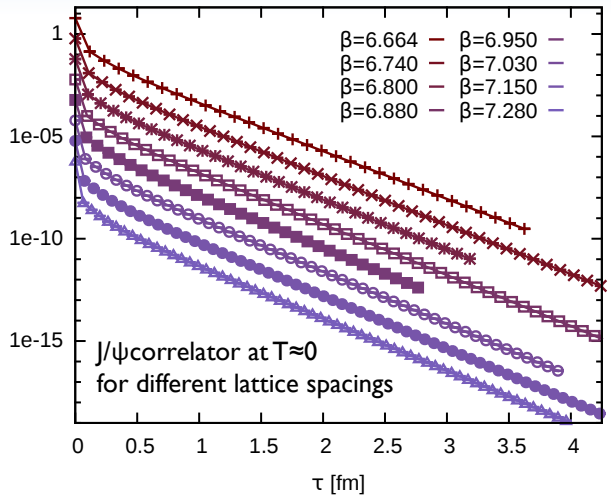

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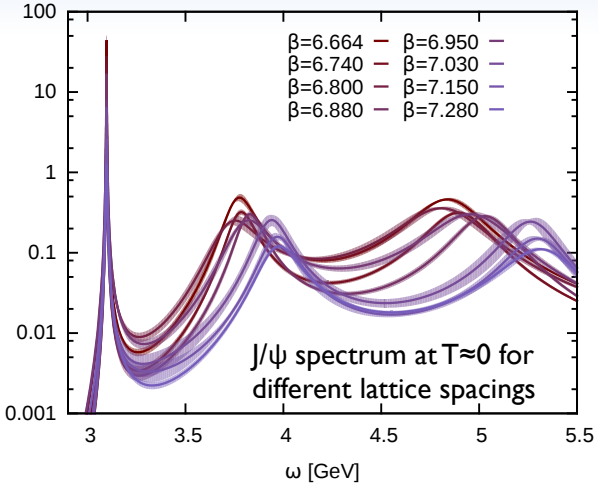


- Inversion of Laplace transform required to obtain spectra: Inherently Ill-defined
- Give meaning to problem by incorporating prior knowledge: Bayesian approach
  - Bayes theorem: Regularize the naïve χ^2 functional P[D|ρ] through a prior P[ρ|I]

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

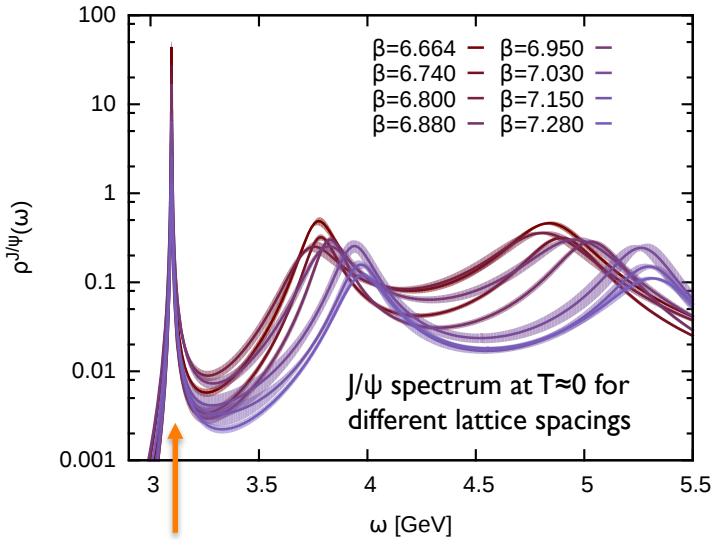
Asakawa, Hatsuda, Nakahara, Prog.Part.Nucl.Phys. 46 (2001) 459

- Recent **progress**: Regulator that remedies flat directions issue in Maximum Entropy Method

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

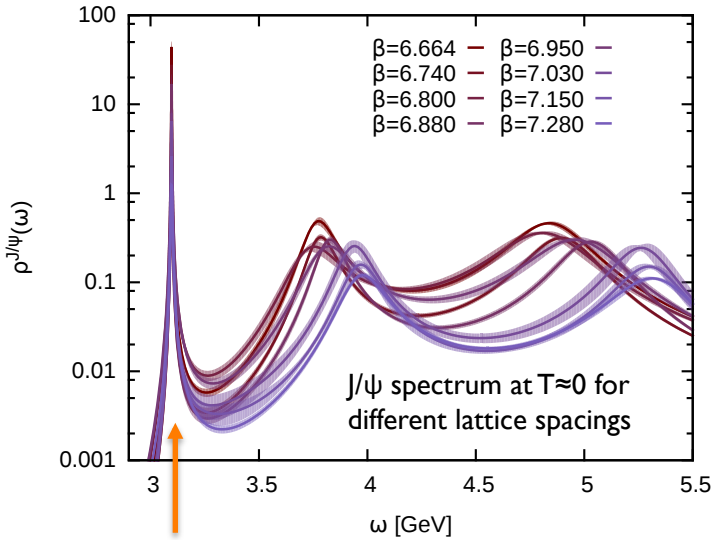
Y.Burnier, A.R. PRL 111 (2013) 18, 182003

Bayesian spectra at T=0



$m_{J/Psi}$ from PDG calibrates freq. scale

Bayesian spectra at T=0



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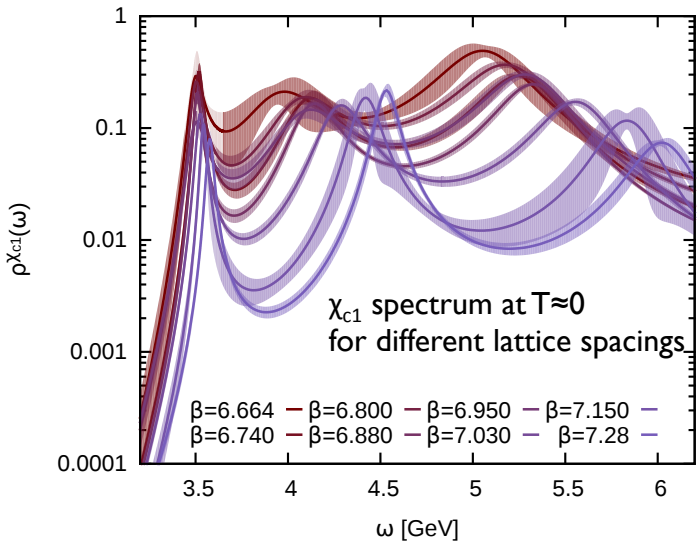

- Check systematic error of lattice computation by postdiction of P-wave ground state mass

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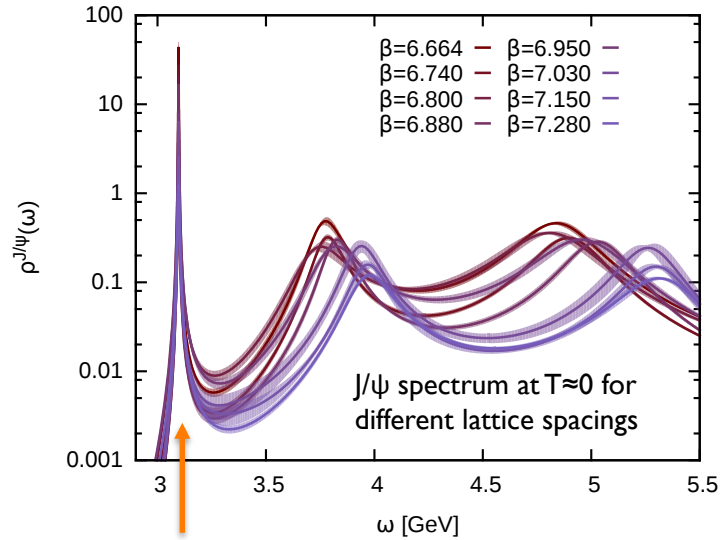

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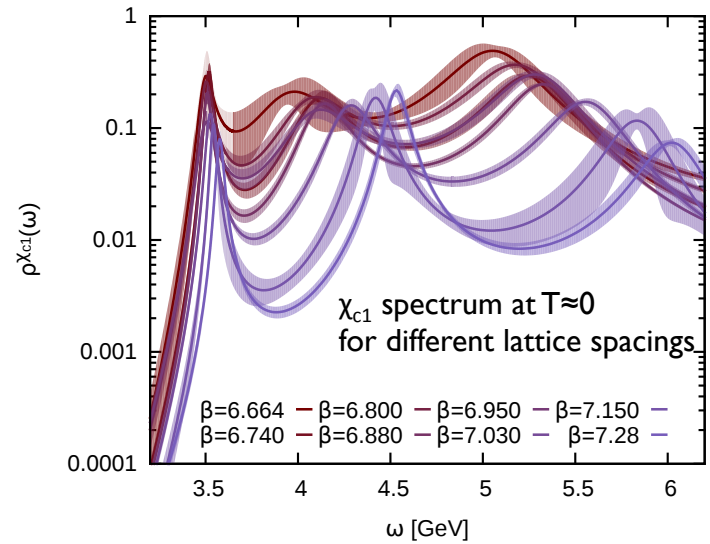
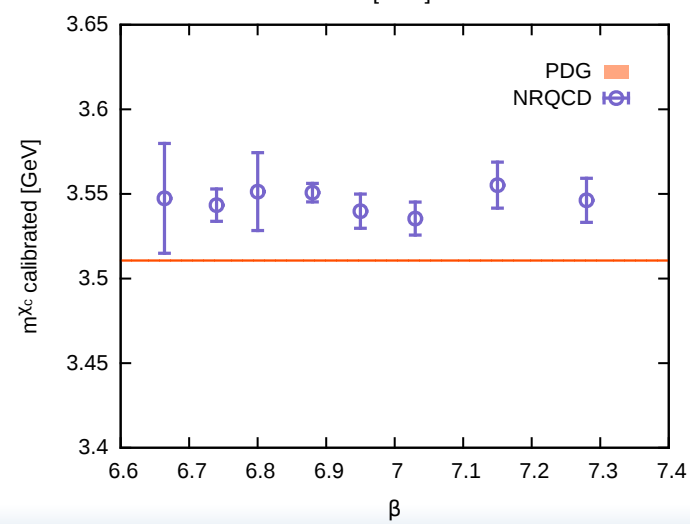


- Check systematic error of lattice computation by postdiction of P-wave ground state mass

$$M_{\chi_{c1}} = 3.546(4)\,\mathrm{GeV} \qquad M^{\mathrm{exp}}_{\chi_{c1}} = 3.51066(7)\,\mathrm{GeV}$$



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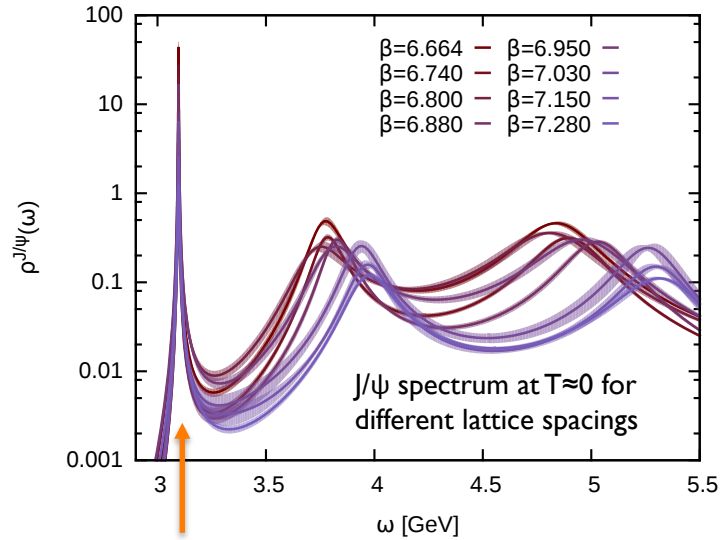

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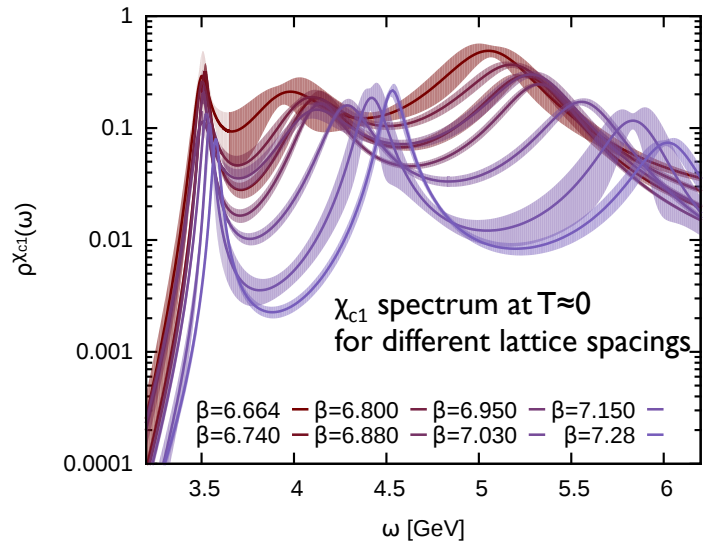

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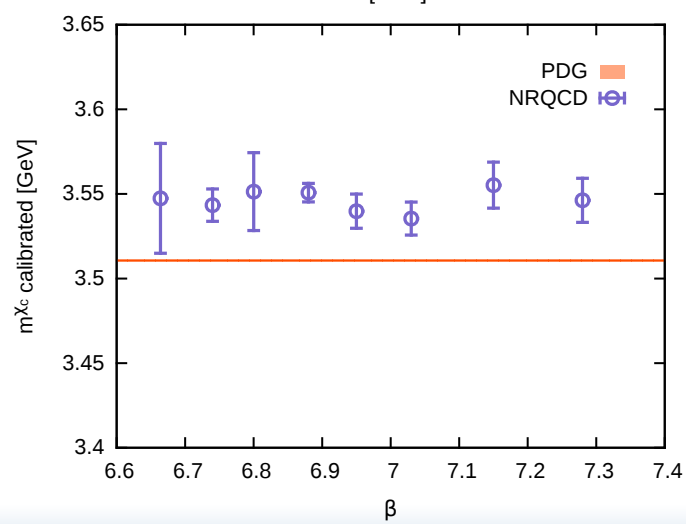

A benchmark for T>0 spectra

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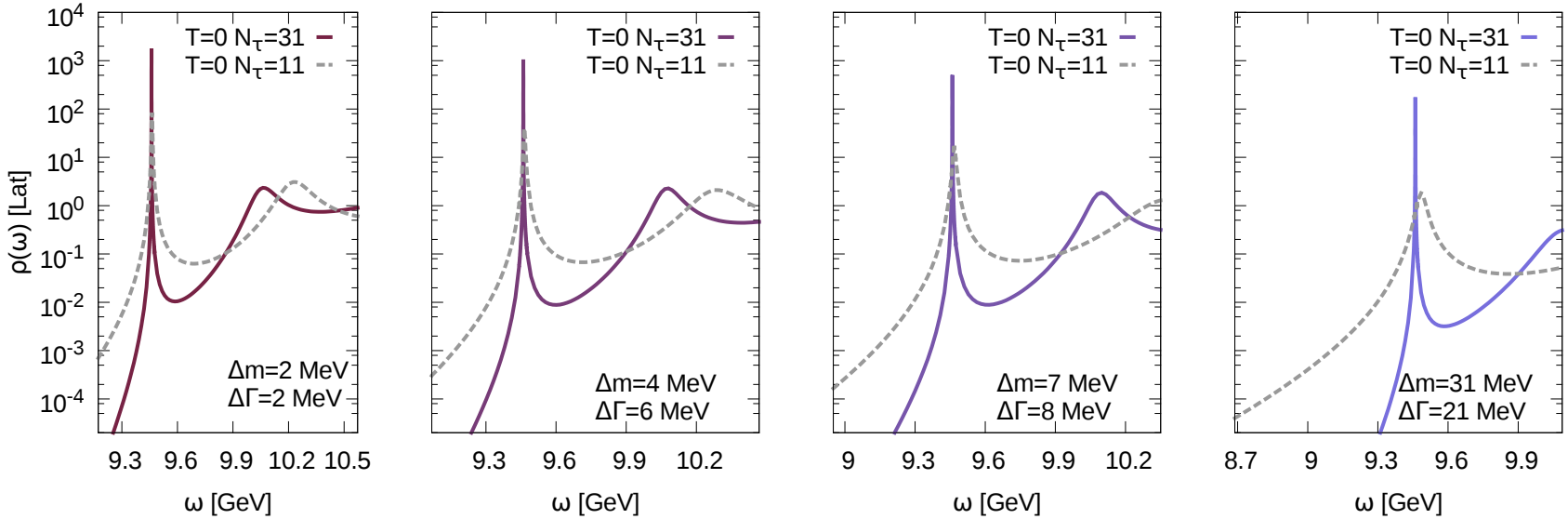

S.Kim, P.Petreczky, A.R.
Phys.Rev. D 91 (2015) 054511

- High precision of the improved Bayesian reconstruction (narrow width resolved)
- How does accuracy suffer from limited available information at T>0 (N_τ=12) ?
- One of the tests we ran: truncate T=0 dataset (N_τ=32/64) to N_τ=12

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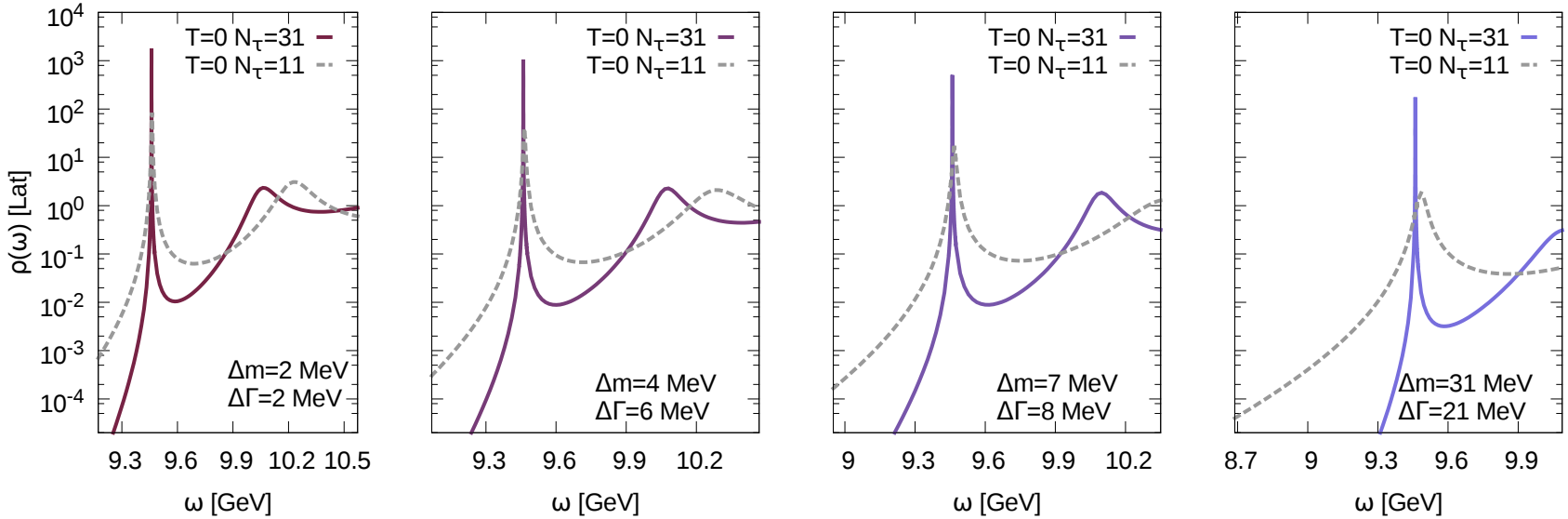

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Example: limits for Upsilon

$$\beta = 6.664: \quad \Delta m_T < 2\text{MeV}, \quad \Delta\Gamma_T < 5\text{MeV}$$

$$\beta = 7.280: \quad \Delta m_T < 40\text{MeV}, \quad \Delta\Gamma_T < 21\text{MeV}$$

Finite temperature results

Sequential in-medium modification

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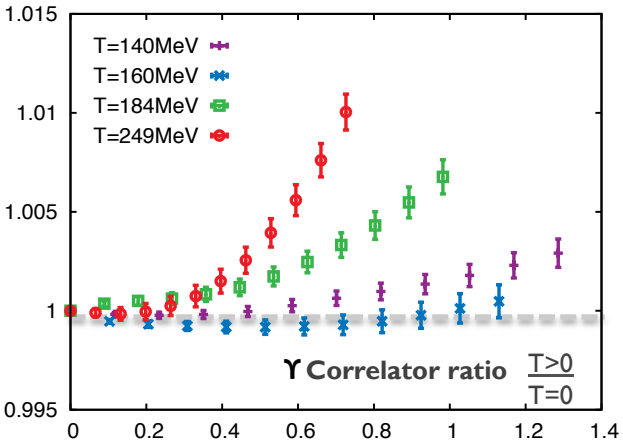
$$E_{\mathrm{bind}}^{T=0} \simeq 1.1\mathrm{Gev}$$



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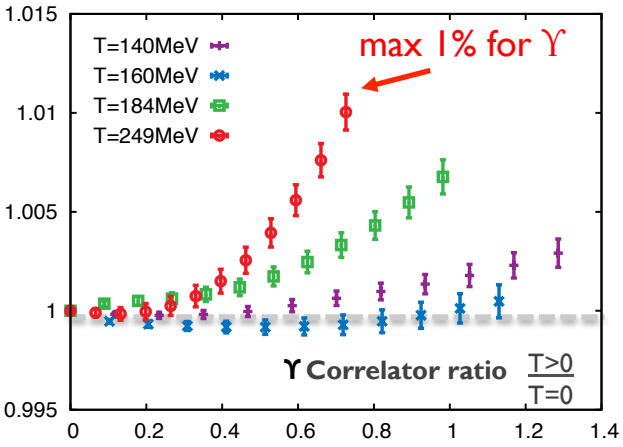

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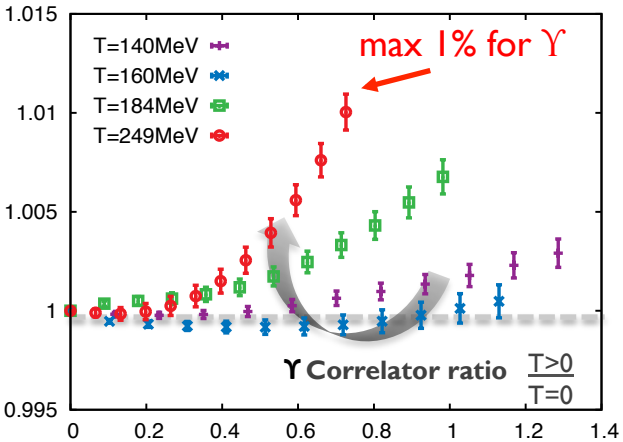

characteristic non-monotonicity

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ZUKUNFT SEIT 1386

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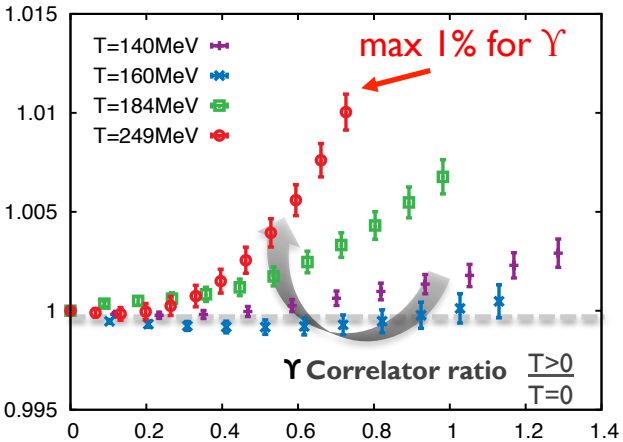

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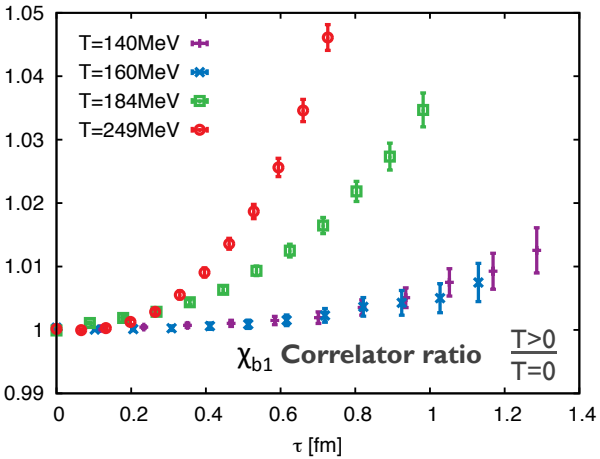

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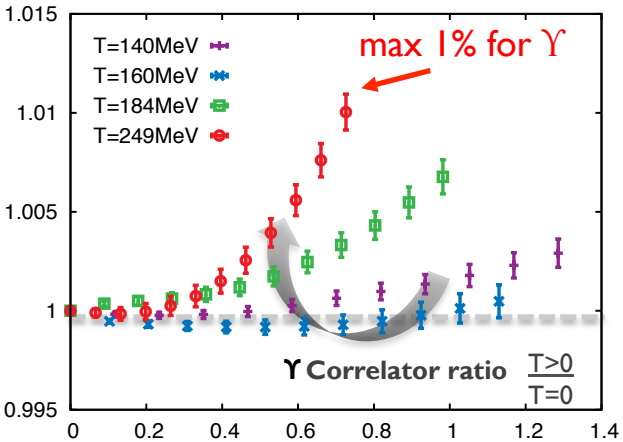

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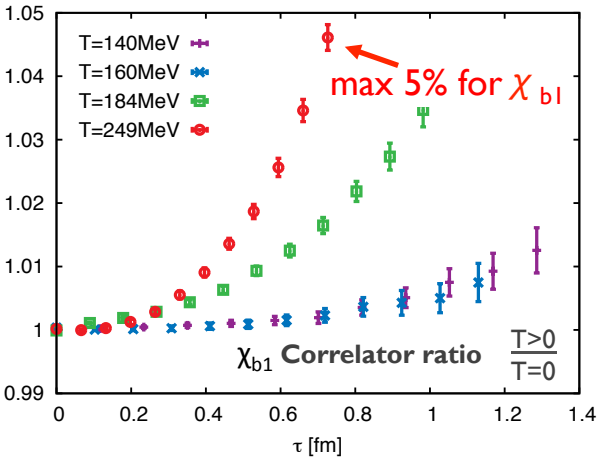

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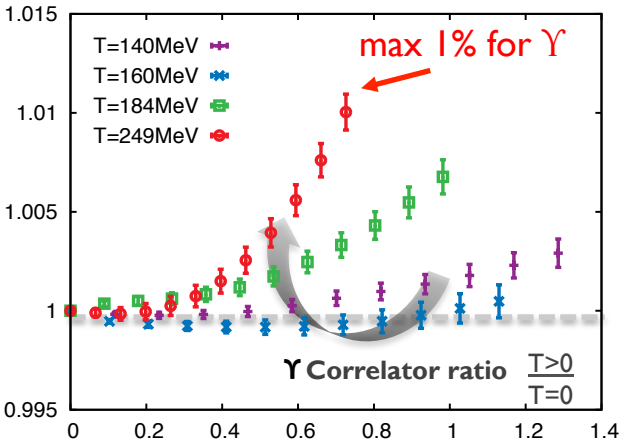

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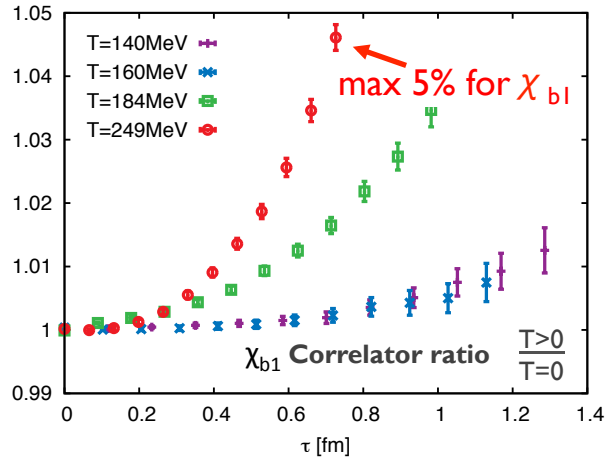

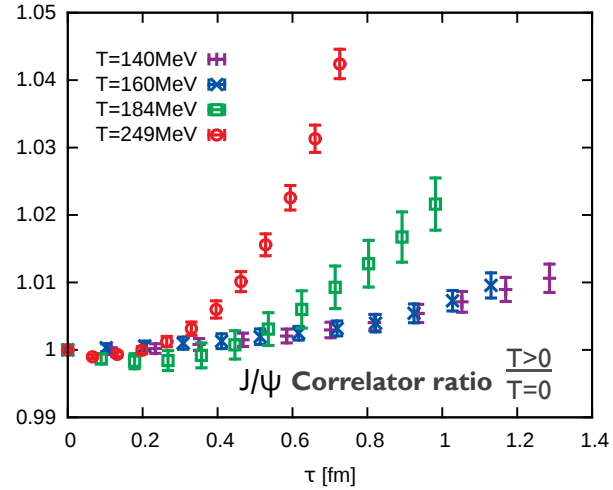

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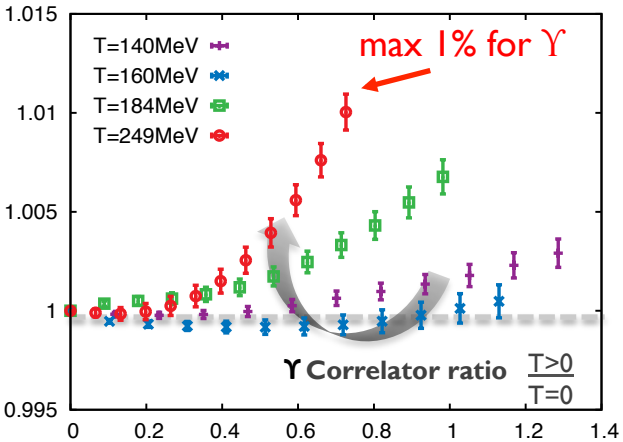

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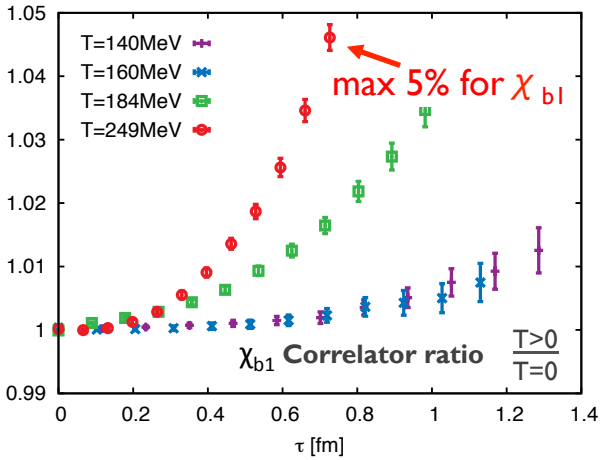

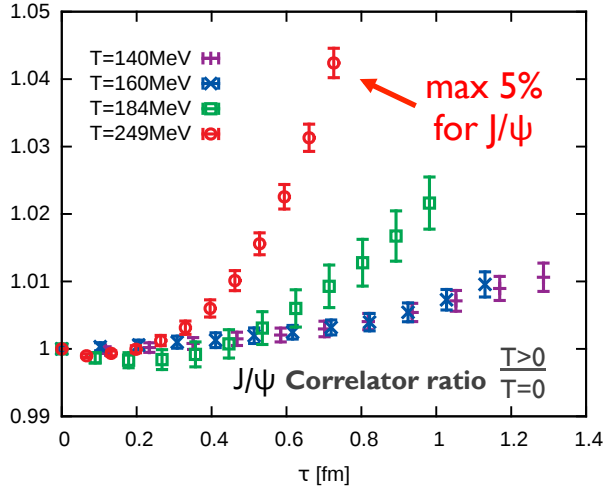

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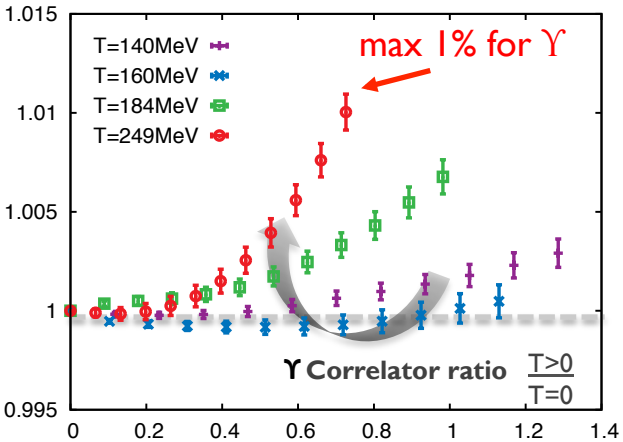

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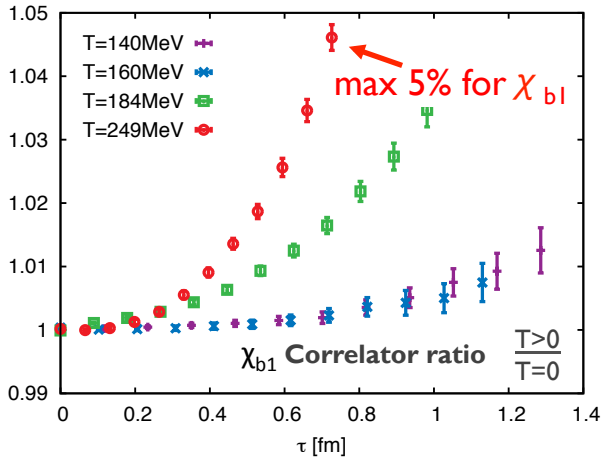

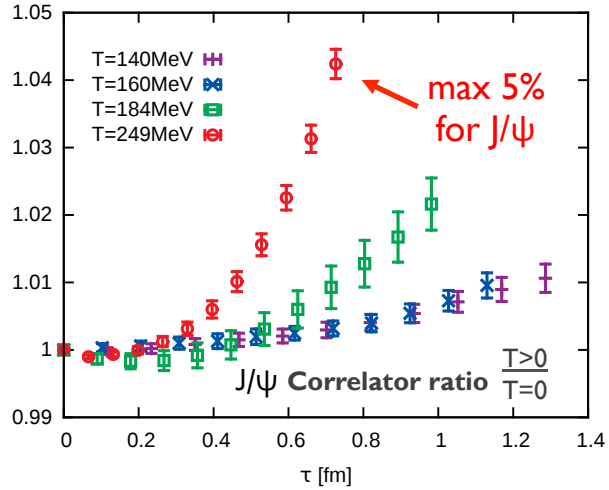

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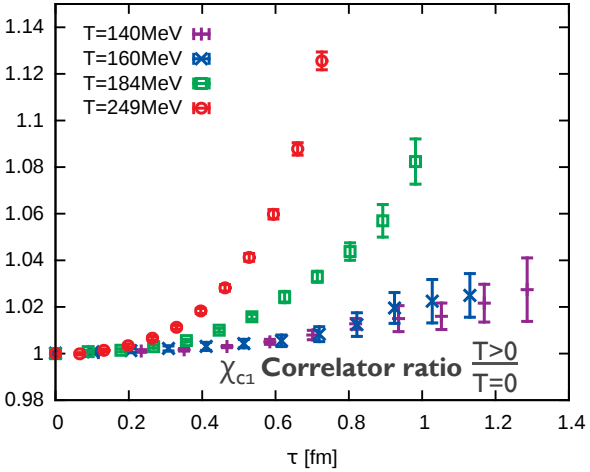

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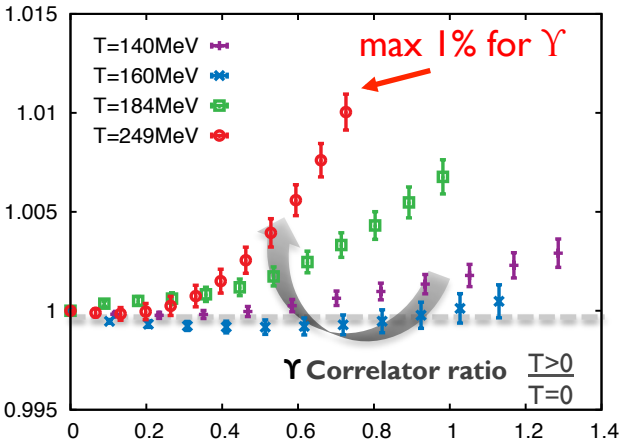

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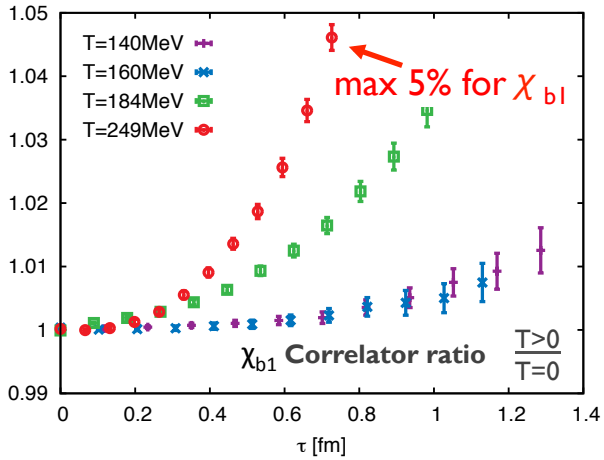

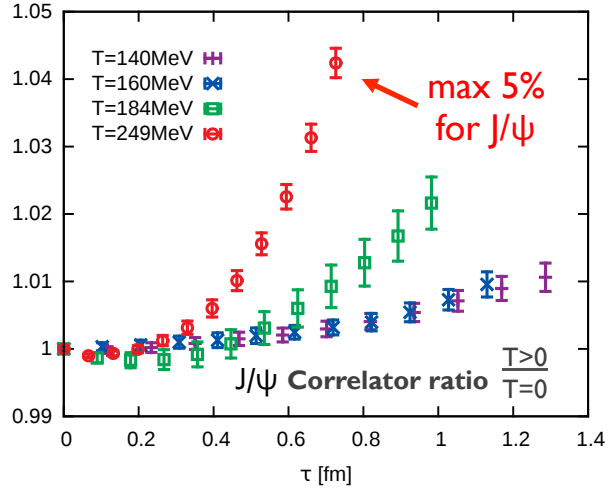

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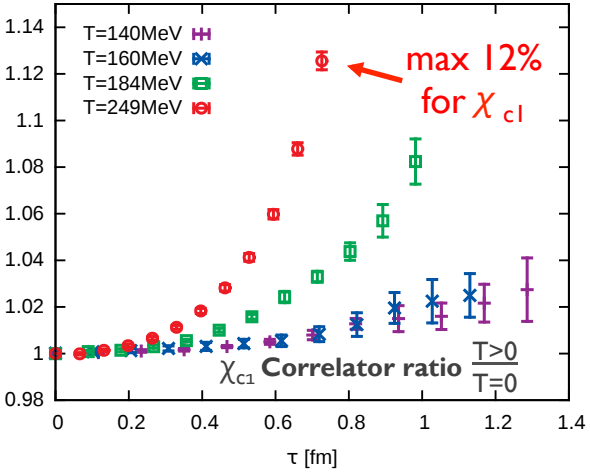

Interpreting lattice correlator ratios

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- Use a phenomenological spectrum to compute correlator ratios

Interpreting lattice correlator ratios

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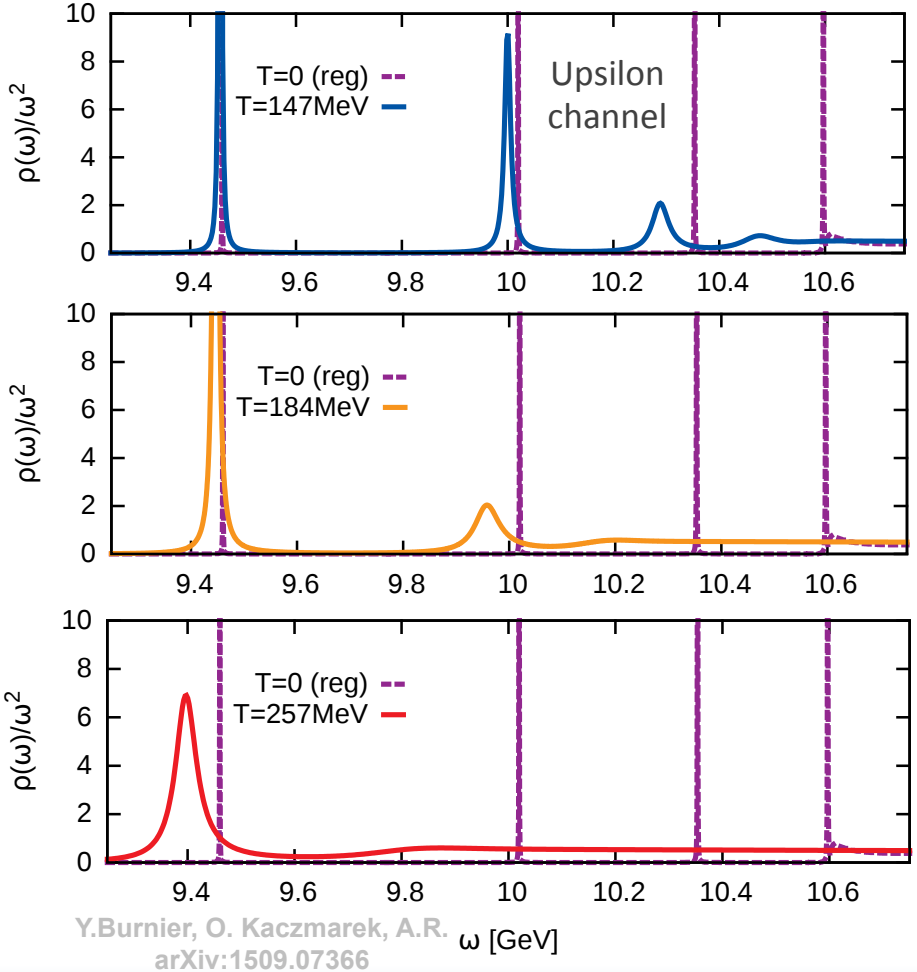
from poster 0021 by Y. Burnier, A.R.



Y.Burnier, O. Kaczmarek, A.R.
arXiv:1509.07366

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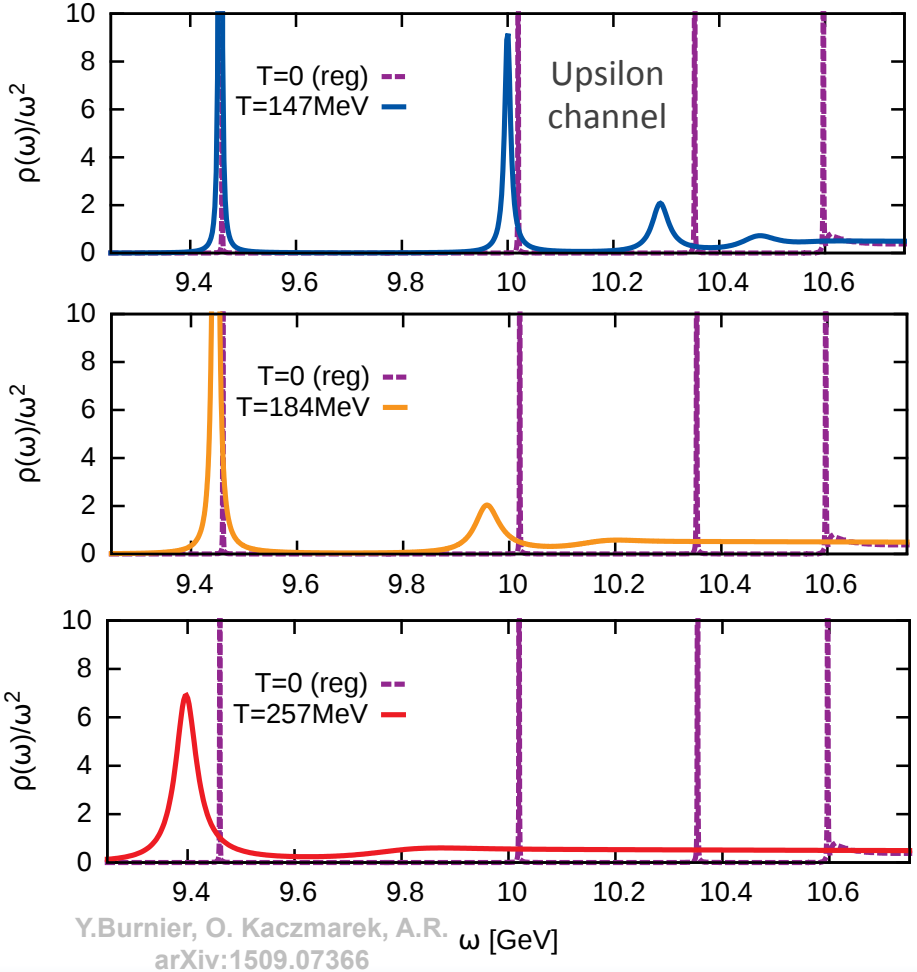

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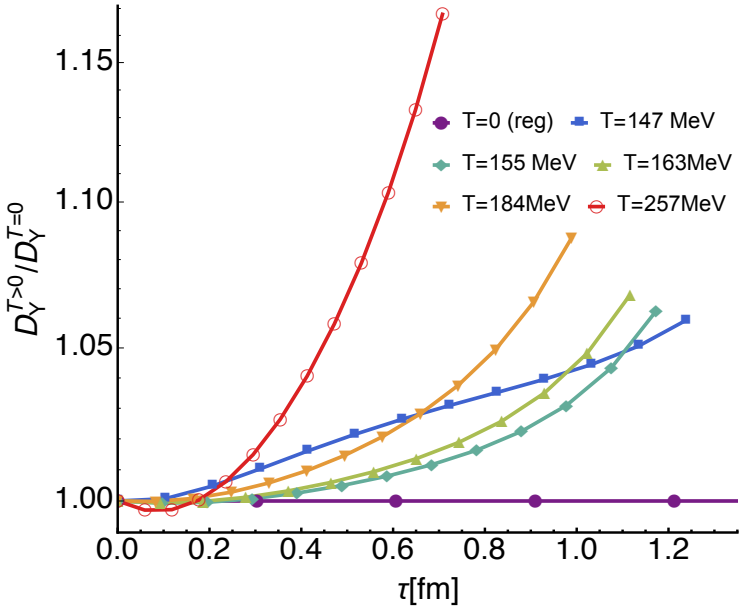

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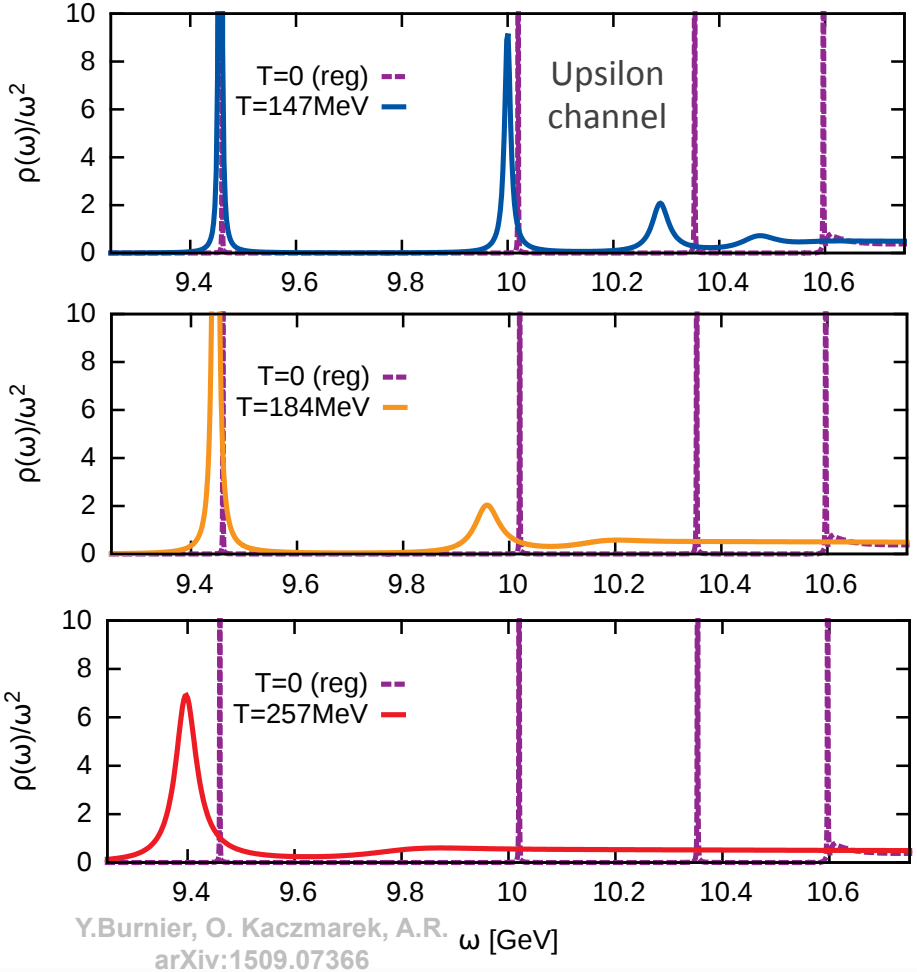

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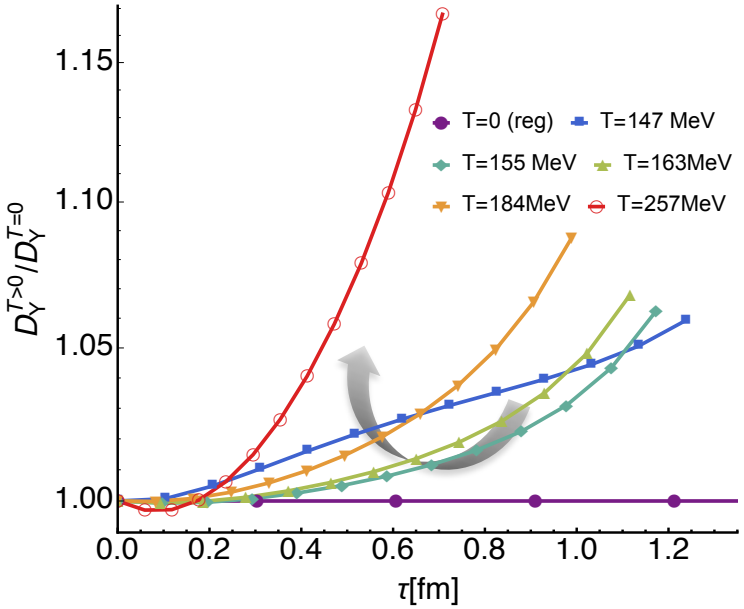

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Bayesian lattice spectra at T>0

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- NRQCD Bottomonium S-wave and P-wave spectra between T= 140 -249MeV

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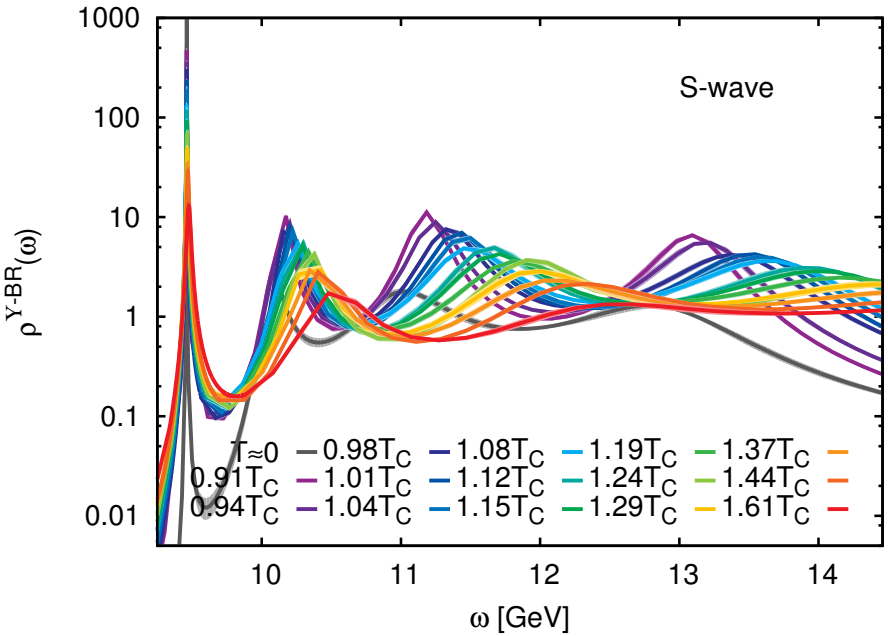

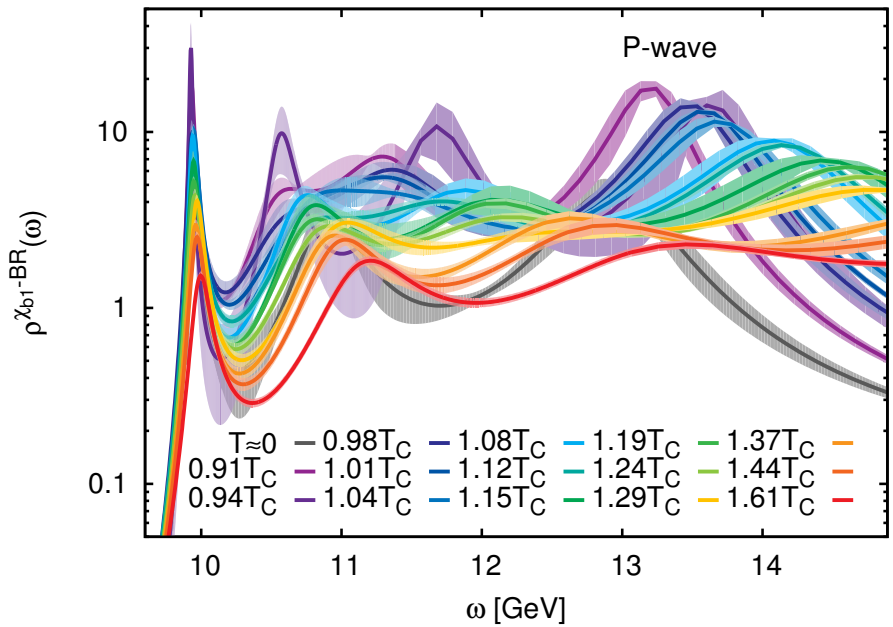

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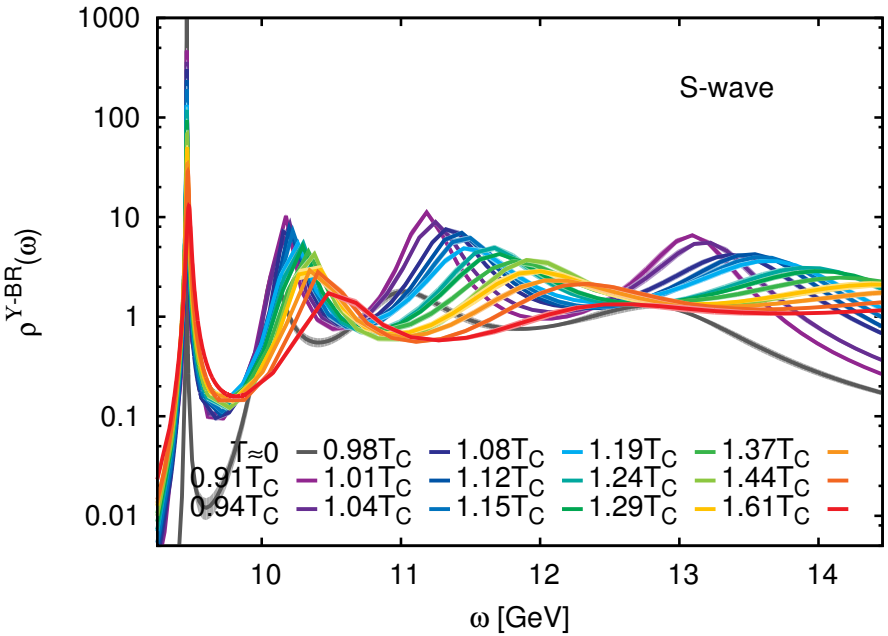

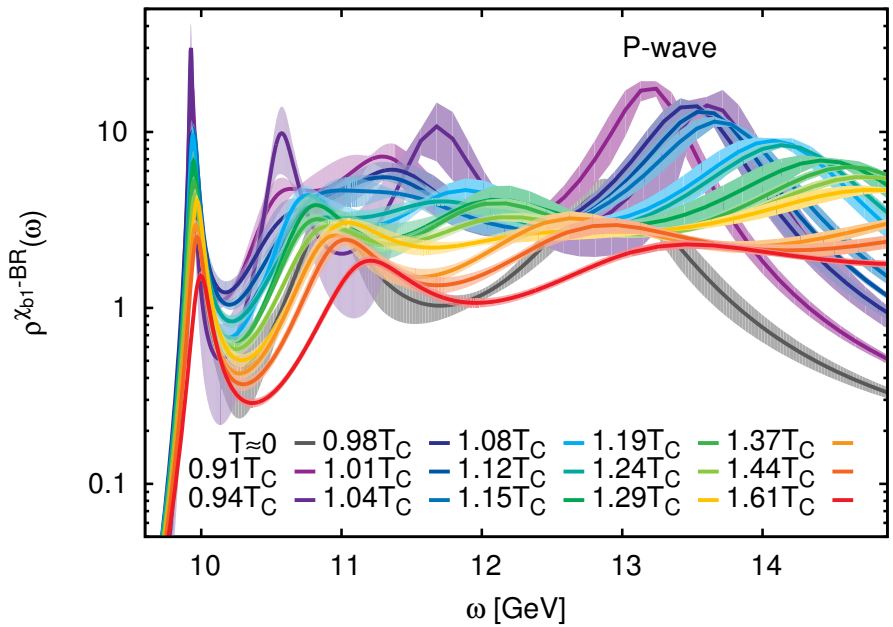

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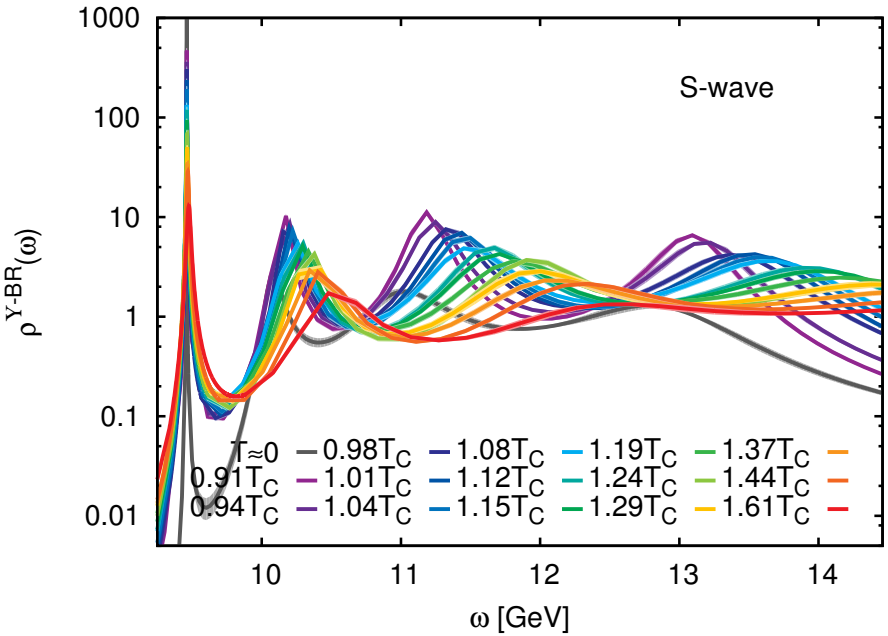

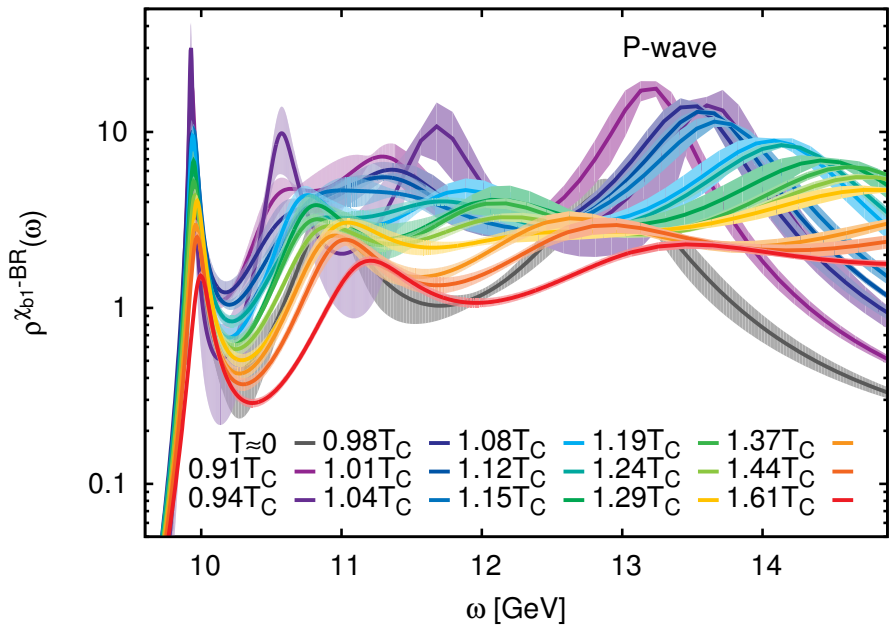

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- S-wave ground state peak present up to T=249MeV
- Naïve inspection by eye fails for P-wave: first vs. second peaked structure

A systematic definition of survival

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- Our strategy: systematic comparison to **non-interacting spectra**

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Analytically known, no peaked features

$$a_\tau E_{\mathbf{p}} = -\log\left(1 - \frac{\mathbf{p}_{\mathrm{lat}}^2}{8 M_b a_s}\right)$$

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G.Aarts et. al., JHEP 1111 (2011) 103

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UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

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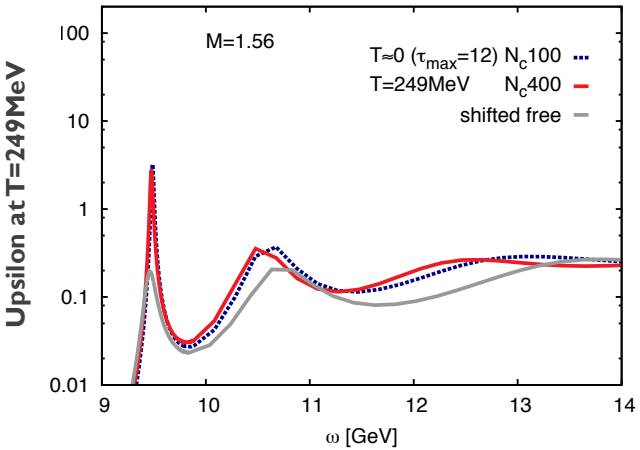
Υ(1S) signal survives at T=249MeV



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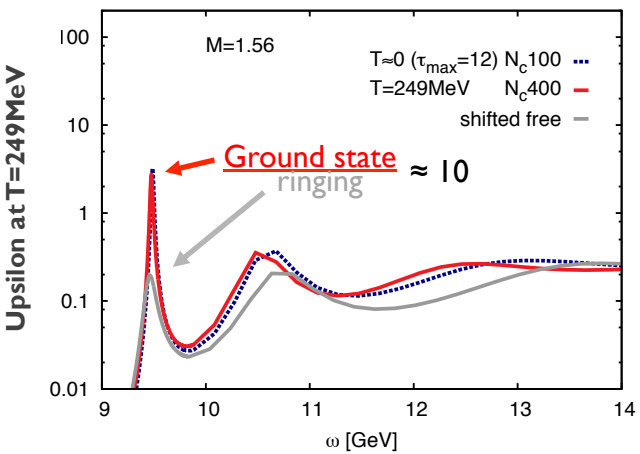

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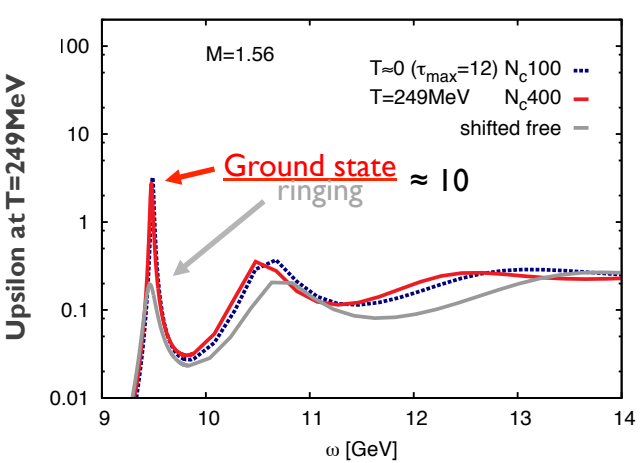
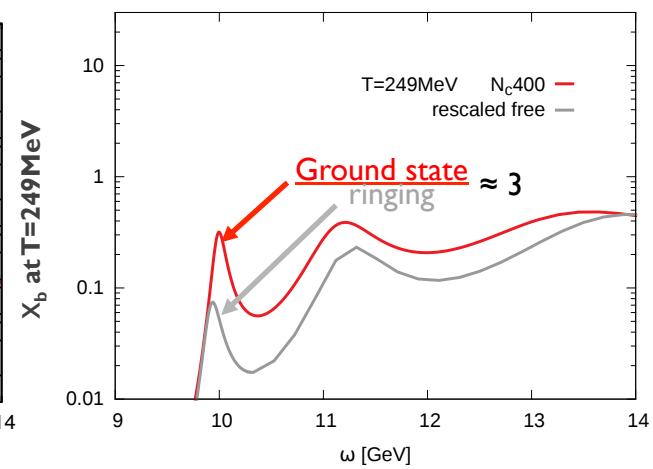


χ_b(1P) signal survives at T=249MeV



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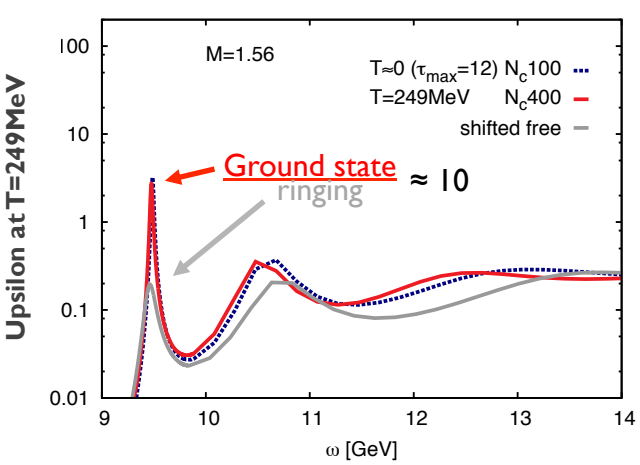

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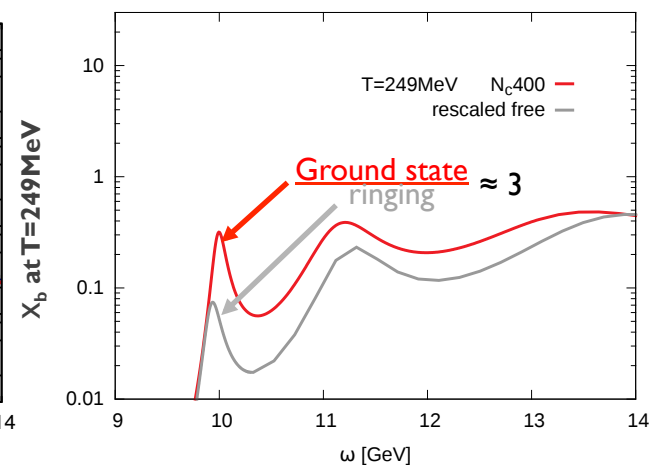
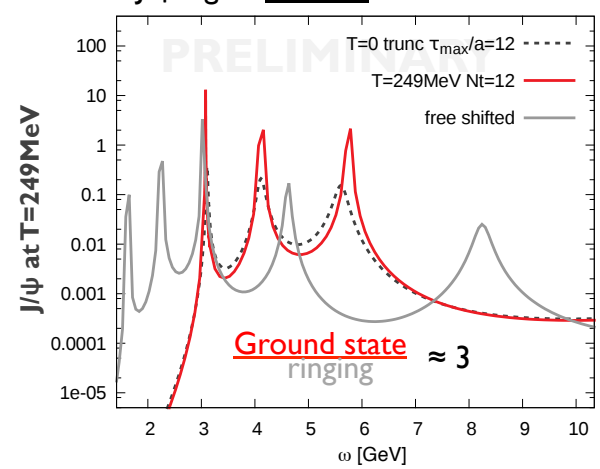


J/ψ signal survives at T=249MeV



Conclusions

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- Combining established EFT methods (NRQCD) and lattice QCD at T>0
  - **Progress I:** Realistic simulations of the QCD medium close to physical point (HotQCD)
  - **Progress II:** Improved Bayesian spectral reconstruction method available
- In-medium results for Quarkonium in lattice NRQCD:
  - **Sequential** in-medium **modification** of correlators according to vacuum E_{bind}
  - In-medium correlator behavior compatible with sequential peak melting
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Thank you for your attention
ご清聴ありがとうございました。