DFG Deutsche Forschungsgemeinschaft

ISOQUANT SFB1225

Spectral properties from the lattice: heavy $Q\bar{Q}$ and imaginary frequency simulations

Alexander Rothkopf
Institute for Theoretical Physics
Heidelberg University

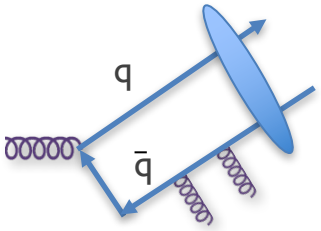
References:

with S.Kim and P. Petreczky	PRD91 (2015) 054511, NPA956 (2016) 713
	in preparation
with J. Pawlowski	arXiv:1610.09531
with J. Pawlowski, F. Ziegler	in preparation

COST - THOR WG1 WORKSHOP - SWANSEA UNIVERSITY - SEPTEMBER 12TH -14TH 2017

Physics motivation

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



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

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

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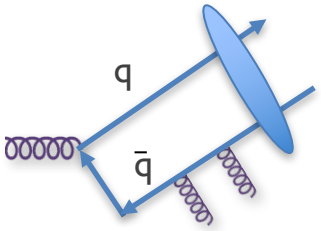

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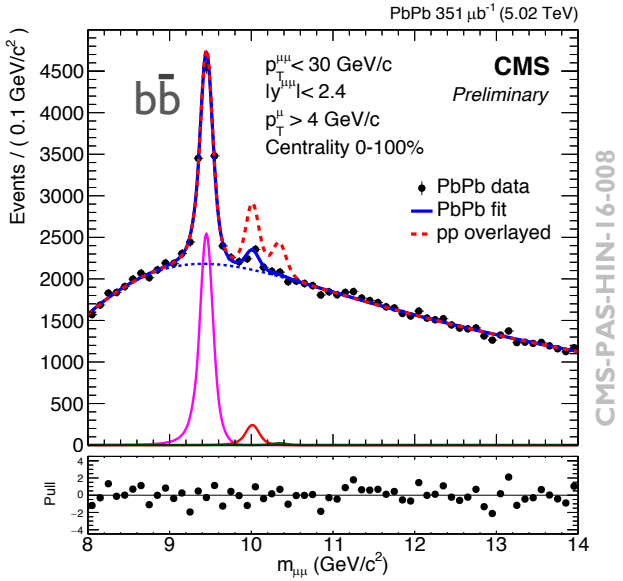

see QM2017 summary by E. Scomparin arXiv:1705.05810

CMS-PAS-HIN-16-008

bb: sampling the full QGP evolution

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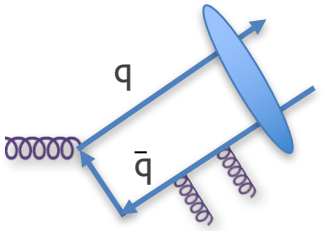

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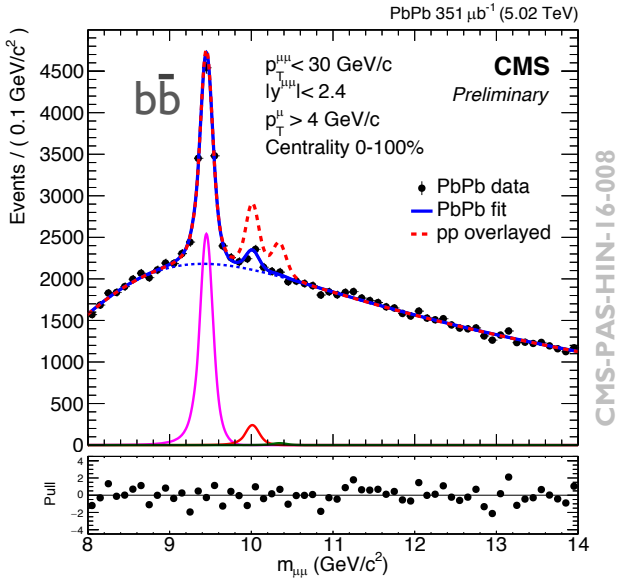

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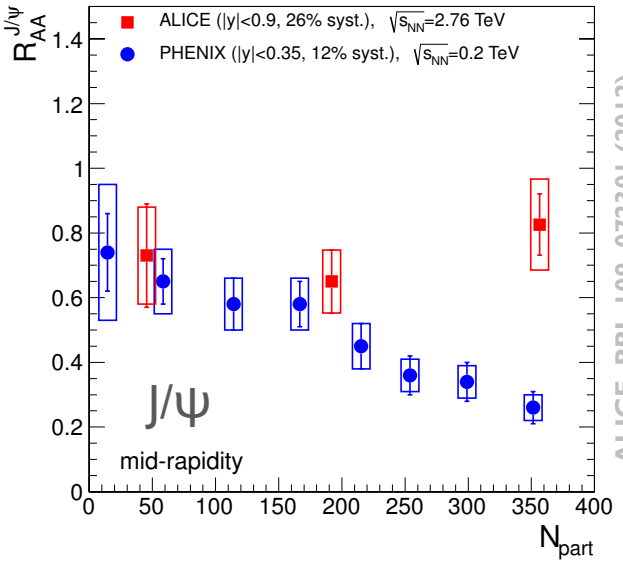

ALICE, PRL 109, 072301 (2012)

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cc: a probe of the late stages

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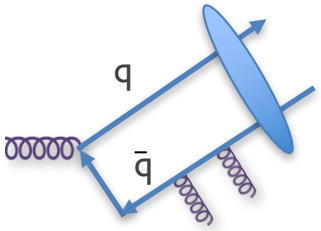

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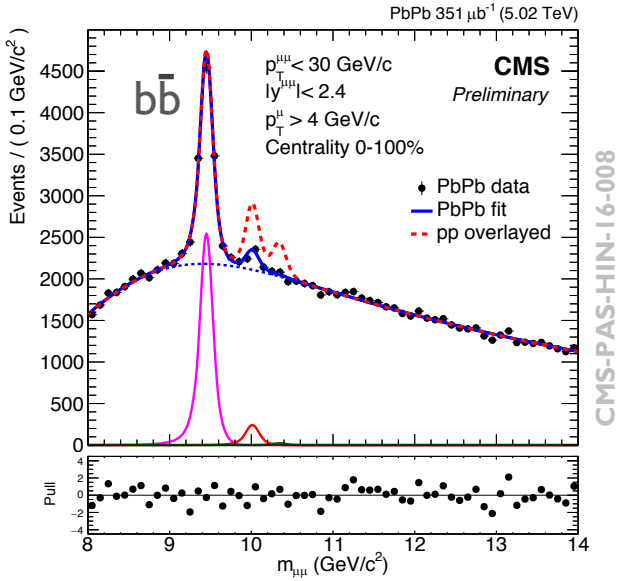

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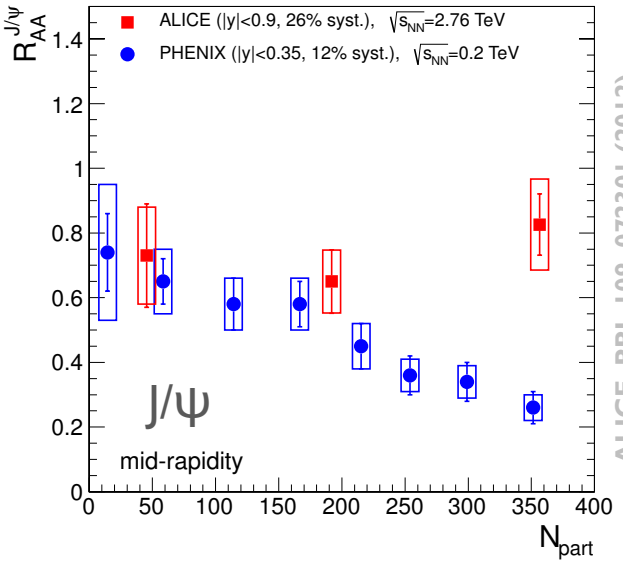

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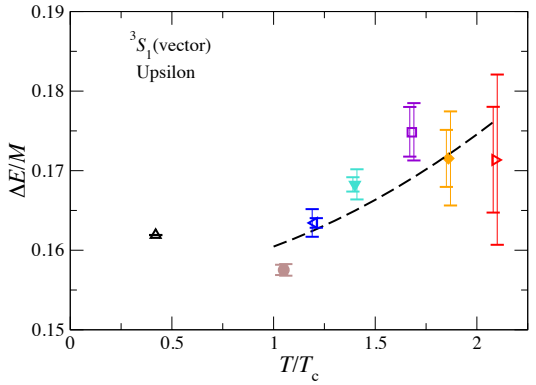
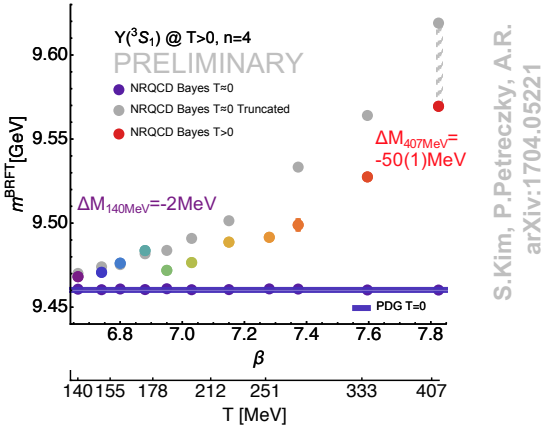
- Goal: first principles insight into heavy-quarkonium in heavy-ion collisions

Theory answer to T>0 S-wave?

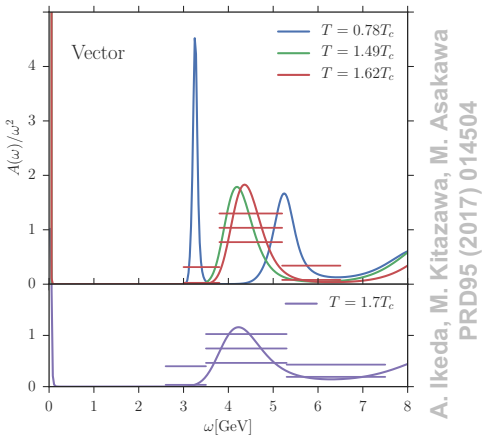
- What is the theory status of in-medium Quarkonium ground state modification ?



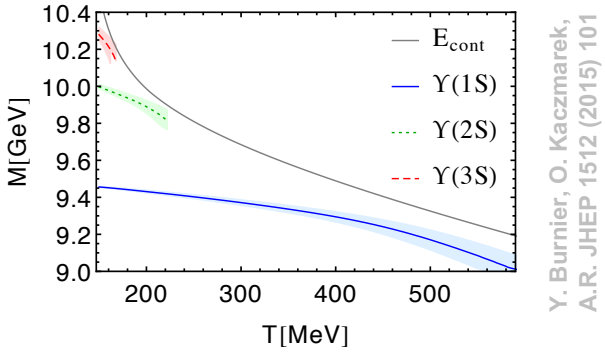
NRQCD MEM (Nf=2+1): bbar mass goes up



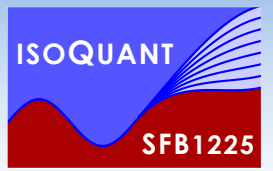
NRQCD BR (Nf=2+1): bbar/ccbar mass goes down



Relativistic MEM (Nf=0): ccbar mass goes up

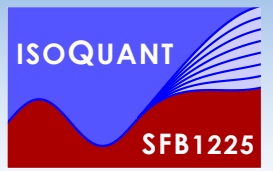


pNRQCD: bbar/ccbar mass goes down



Outline

- Motivation
  - Coherent picture of in-medium heavy-quarkonium from the lattice
- In-medium quarkonium from a lattice EFT (NRQCD)
  - Numerical setup and spectral reconstruction
  - Current T>0 results from realistic full QCD simulations
- Towards improved spectral information from thermal fields
  - Derivation of a novel simulation prescription
  - Current exploratory results from toy models to quenched QCD
- Conclusion



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Heavy quarks on the lattice

Relativistic treatment of light
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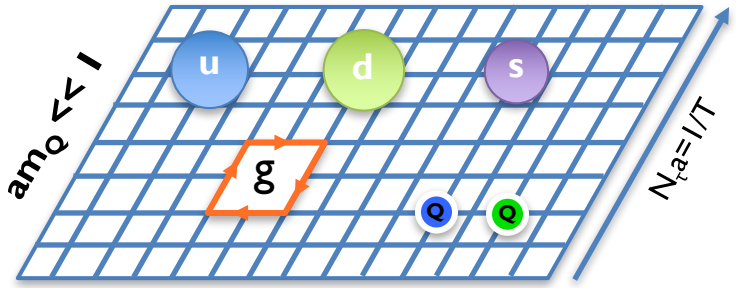

Full Lattice QCD simulation incl. $Q\bar{Q}$
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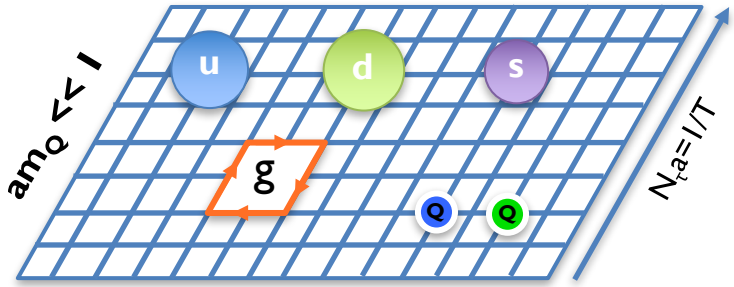

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$$\frac{\Lambda_{QCD}}{m_Q} \ll 1$$

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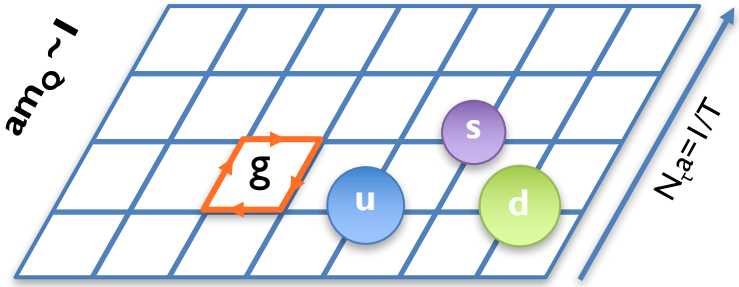

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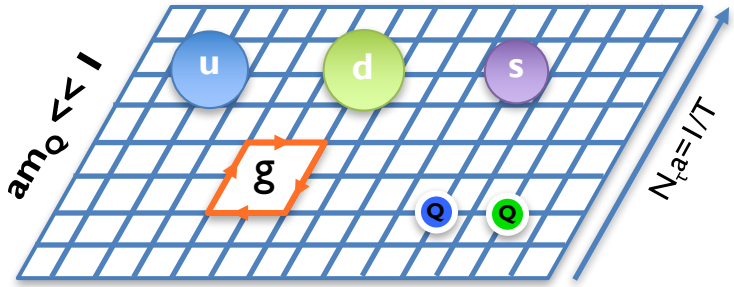

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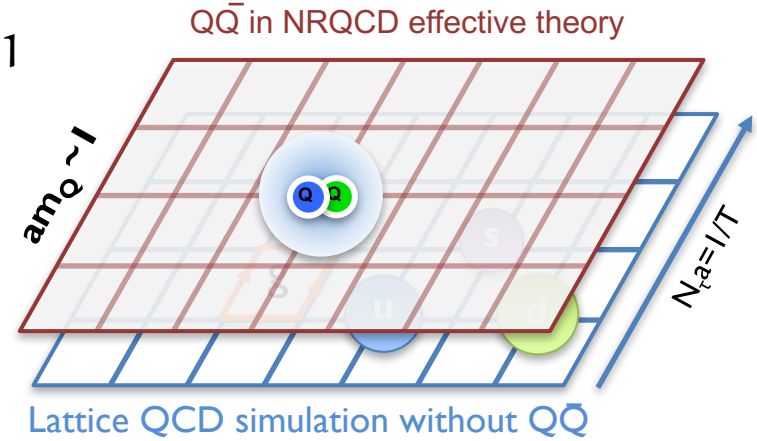

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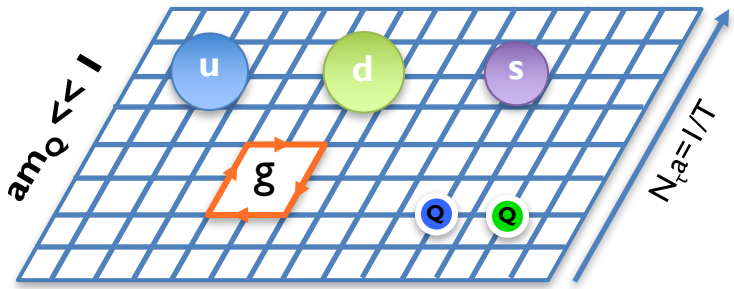

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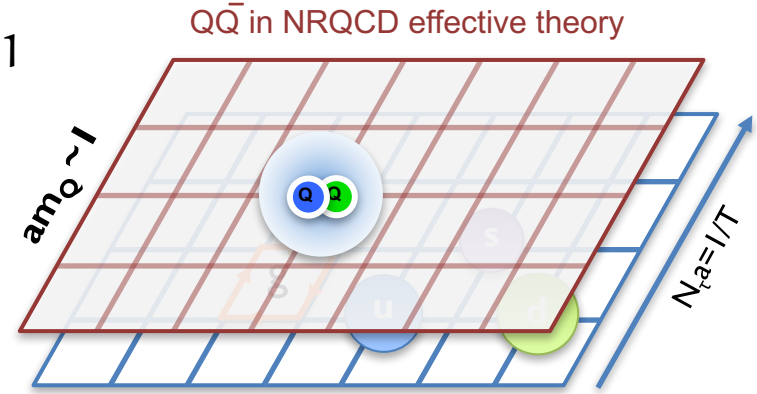

Lattice QCD simulation without QQ̄

- 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 (bb̄ n=4, cc̄ n=8)

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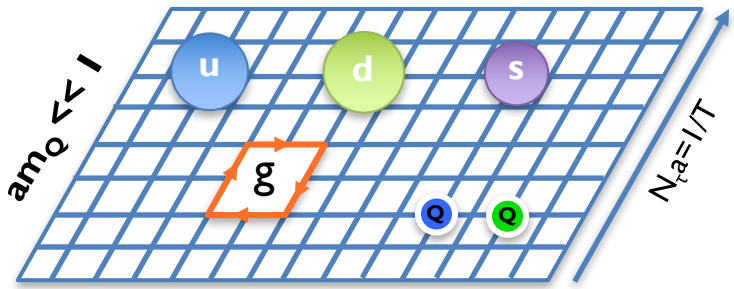

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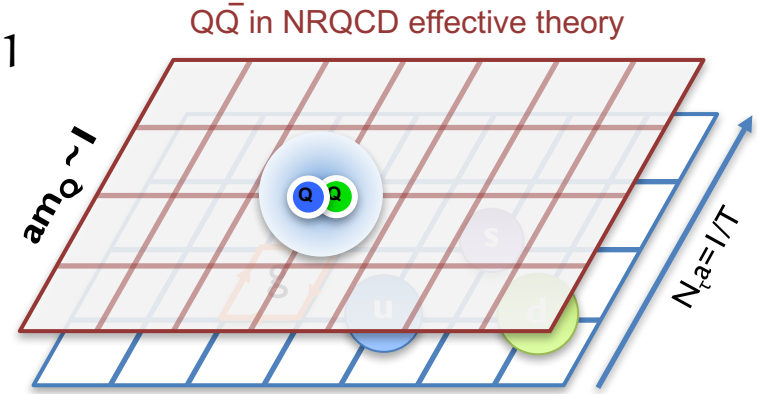

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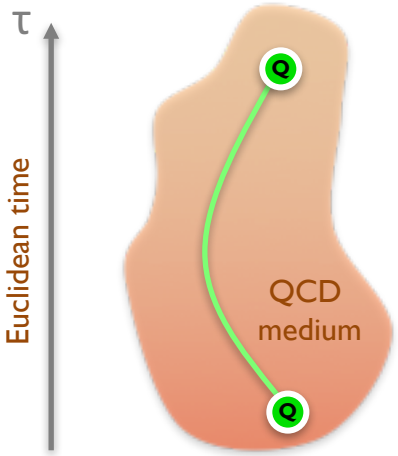
  - adaptive discretization in temporal direction: Lepage parameter n ($b\bar{b}$ n=4, $c\bar{c}$ n=8)
- Realistic simulations of the QCD medium by HotQCD with extended T range
  HotQCD PRD85 (2012) 054503, PRD90 (2014) 094503
  - $48^3 \times 12$ m_π=161MeV (β=6.664-7.825) $M_b a$= [2.759 – 0.954] T= [140 – 407] MeV $M_c a$= [0.757 – 0.42] T= [140 – 251] MeV

Correlation functions in NRQCD



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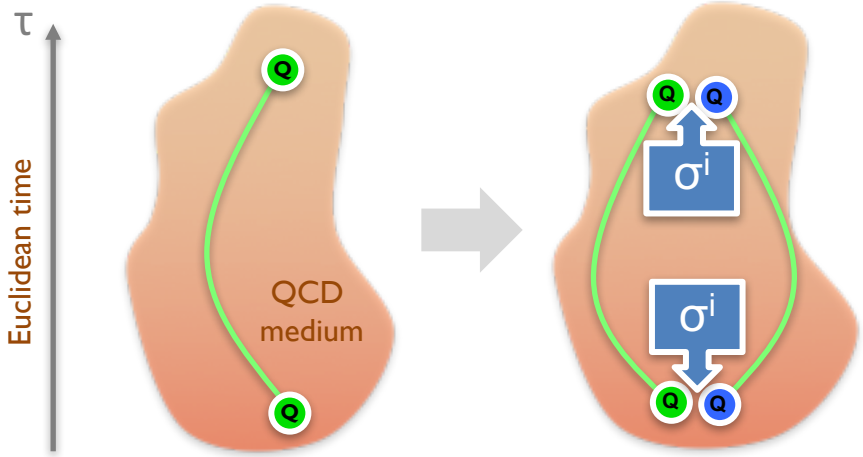

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$D_{J/\psi}(\tau) \triangleq \langle \psi_{J/\psi}(\tau) \psi^{\dagger}_{J/\psi}(0) \rangle$ “

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

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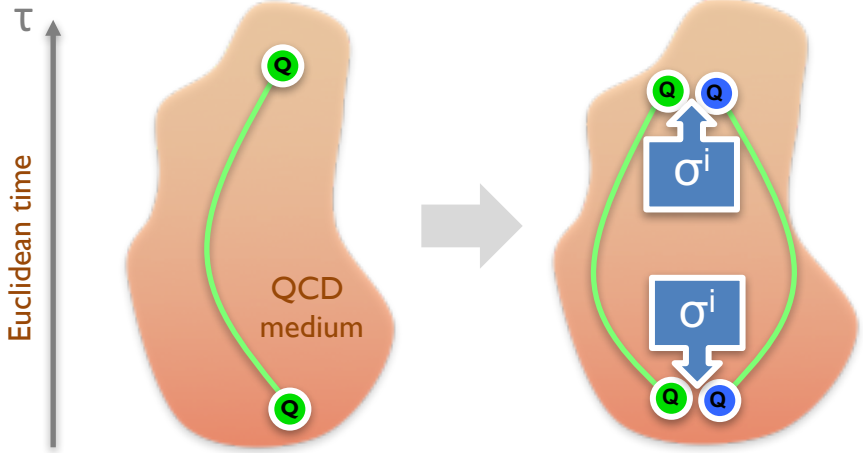

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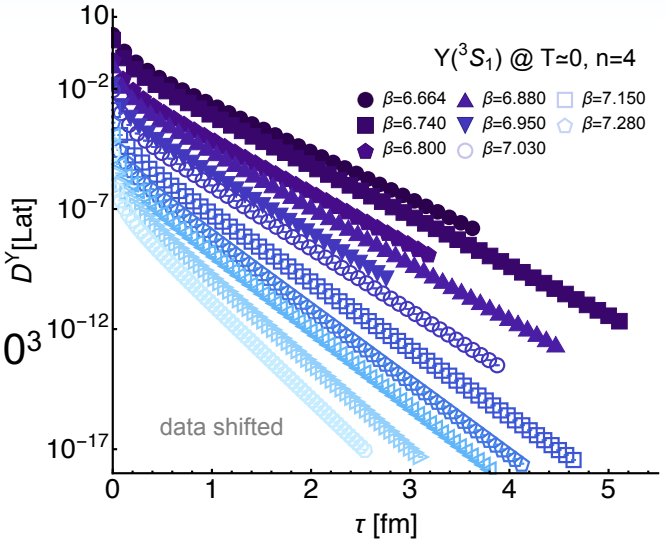
$N_{bb}^{meas}(T>0)=1\text{-}4\times10^3$



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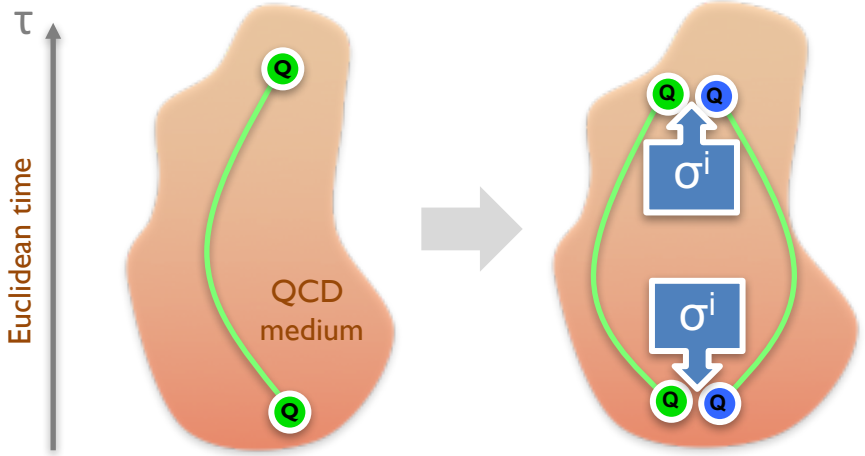

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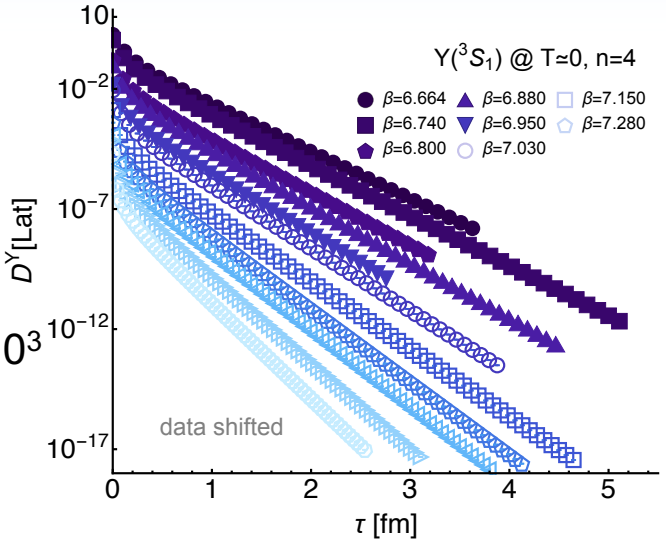

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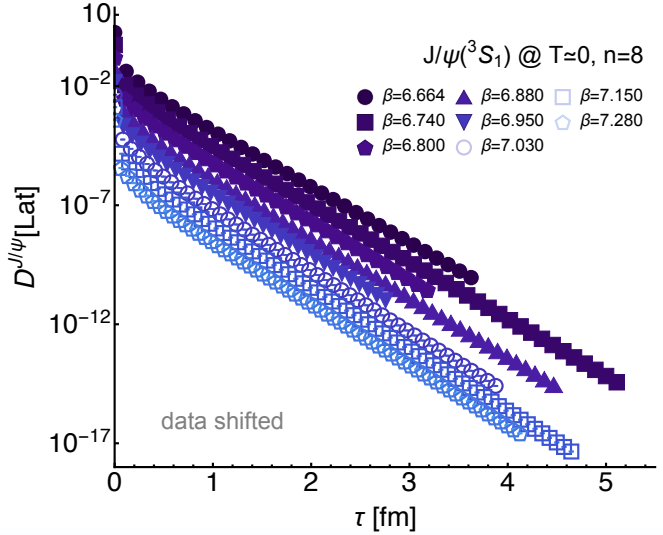

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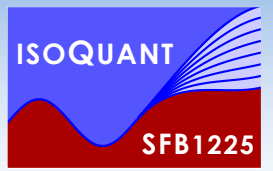

Accessing spectral functions

- Inversion of Laplace transform required to obtain spectra from correlators

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

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

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

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

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

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

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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. data D_i has finite precision

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

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

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

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

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

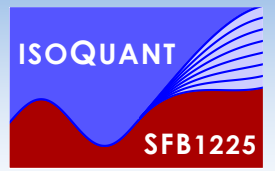
$$P[\rho|I] \propto e^S \qquad S = \alpha \sum_{l=1}^{N_\omega} \Delta\omega_l \left(1 - \frac{\rho_l}{m_l} + \log\left[\frac{\rho_l}{m_l}\right]\right)$$

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

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

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

An improved Bayesian strategy



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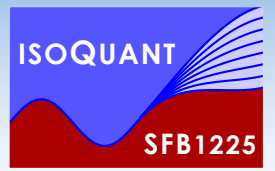

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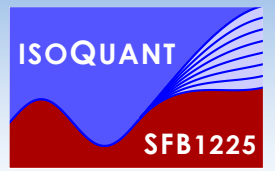

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$$S_{BR} = \alpha \int d\omega \left(1 - \frac{\rho}{m} + \log\left[\frac{\rho}{m}\right]\right)$$

- 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

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- 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

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

see e.g. C. Fischer, J.M. Pawlowski, A.R., C. Welzbacher arXiv:1705.03207

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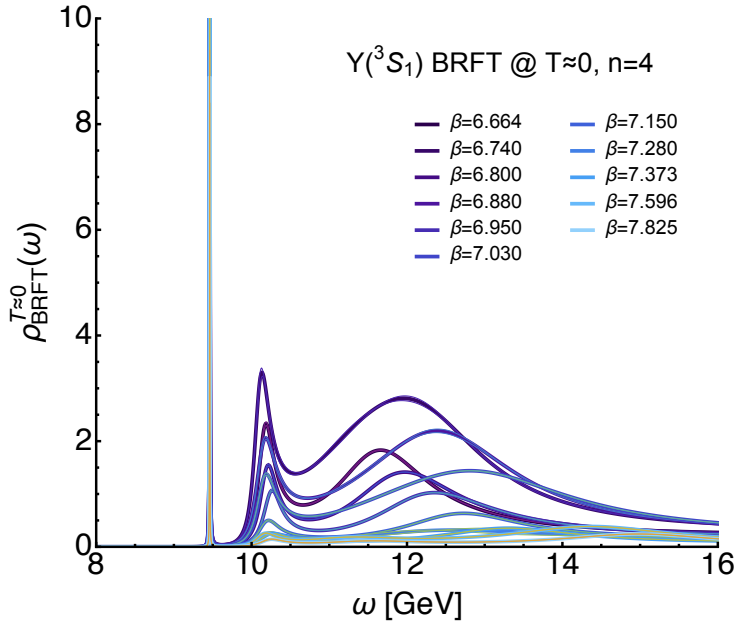
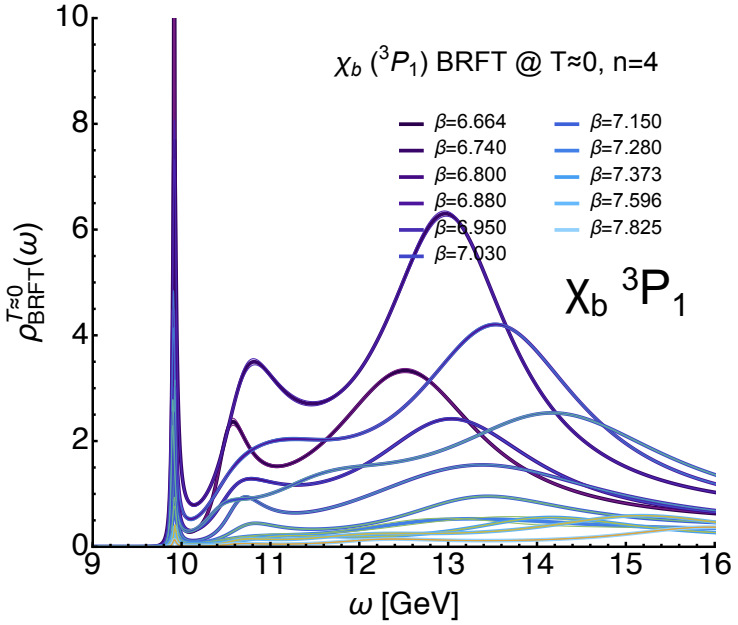
Bayesian spectra at T=0

- BR reconstruction exhibits strong ground state signal, shows signs of excited state





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

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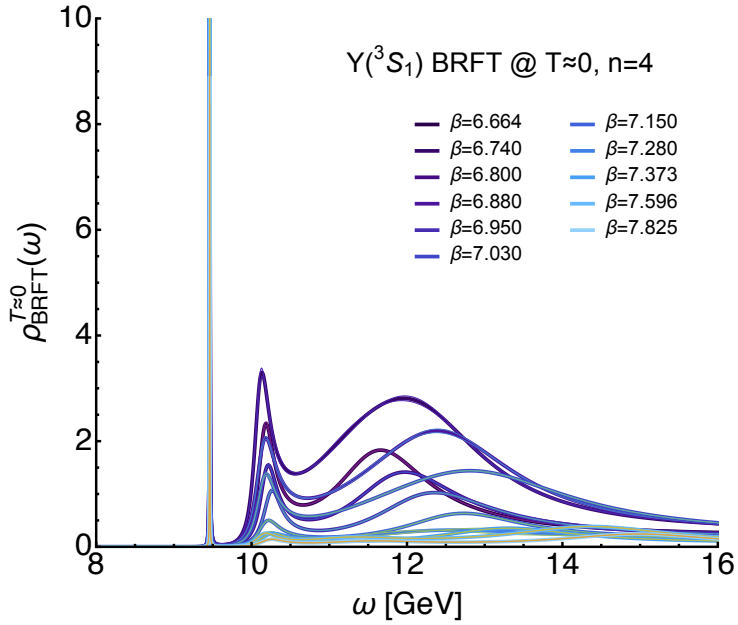

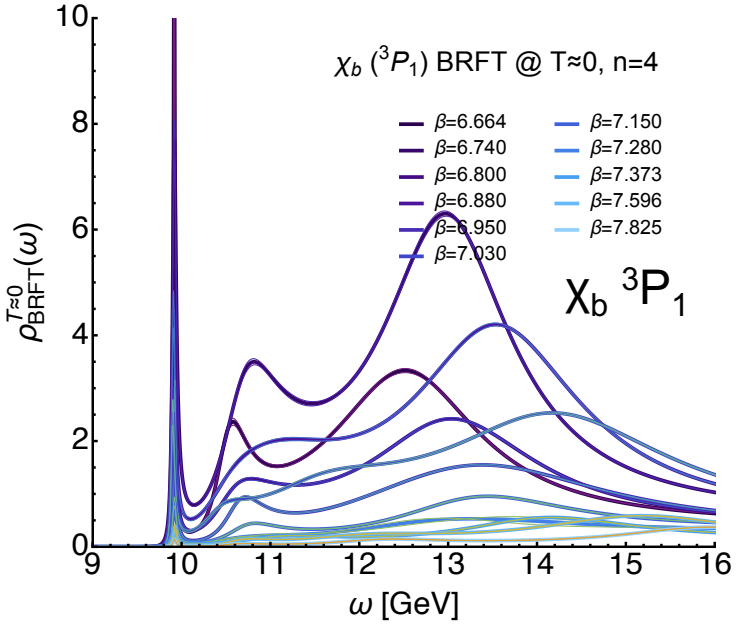

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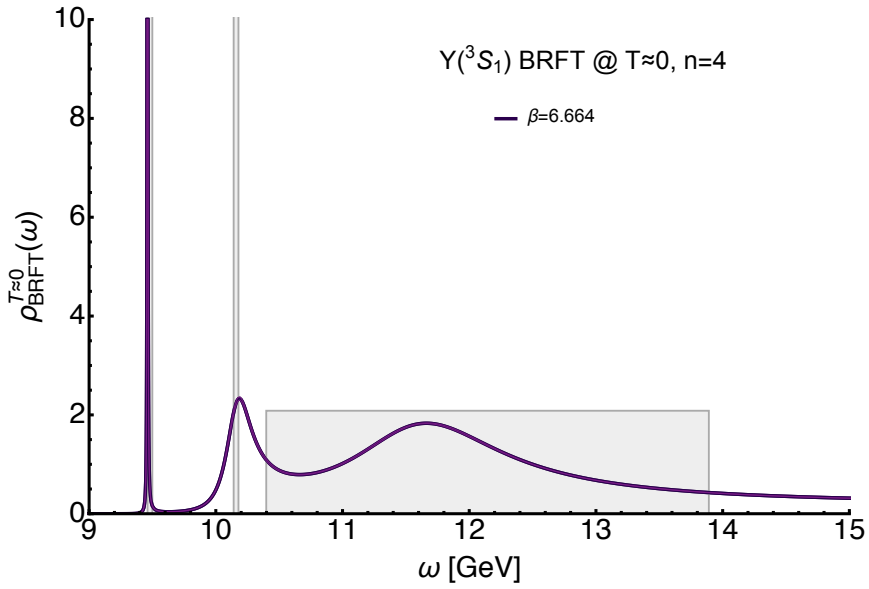

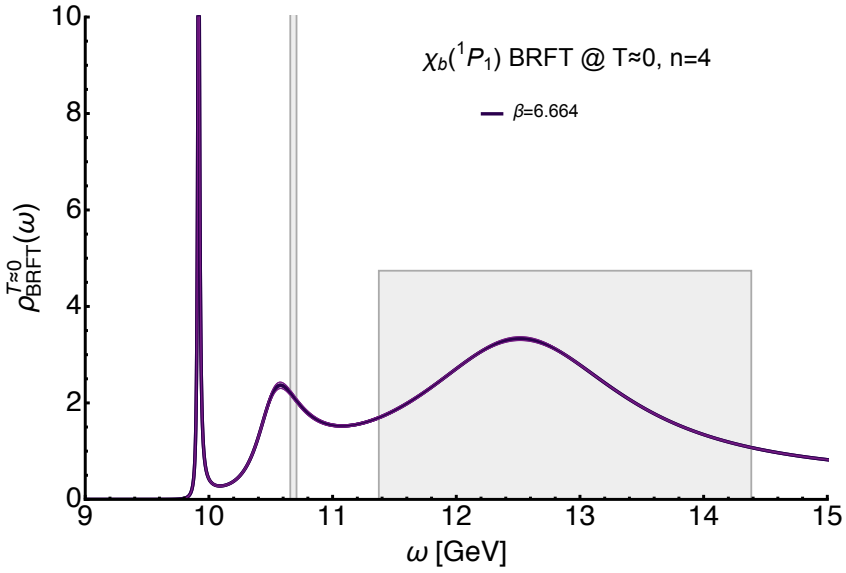

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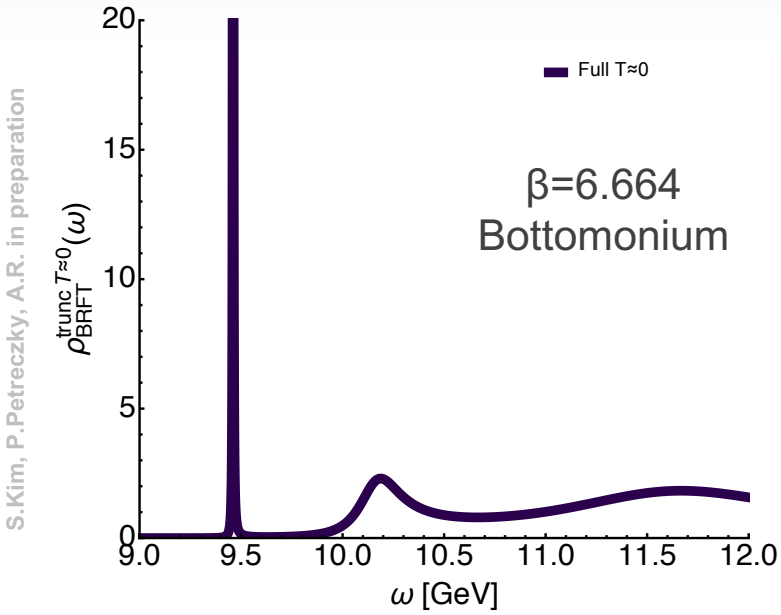
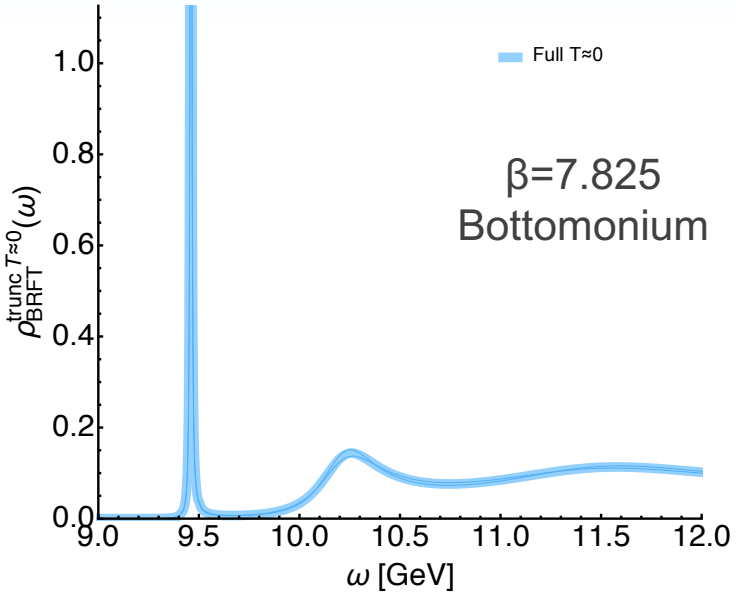
Taking control of systematics I





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

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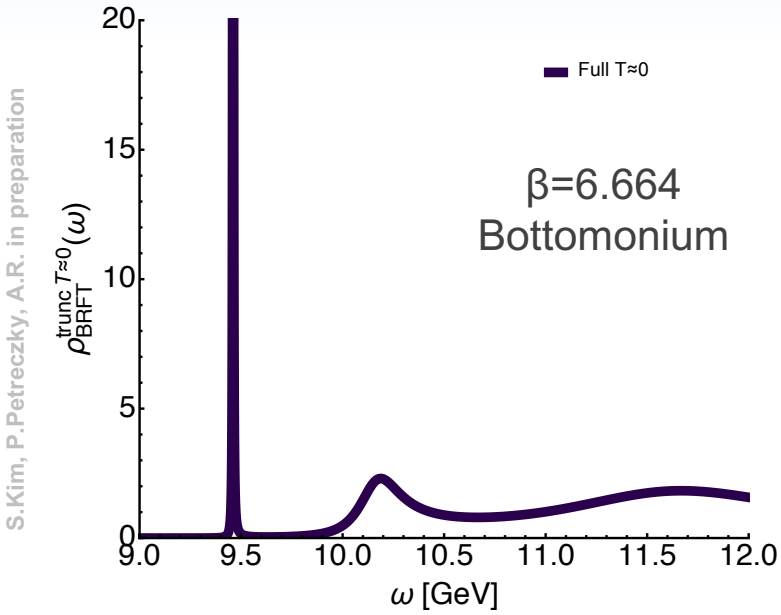
Taking control of systematics I



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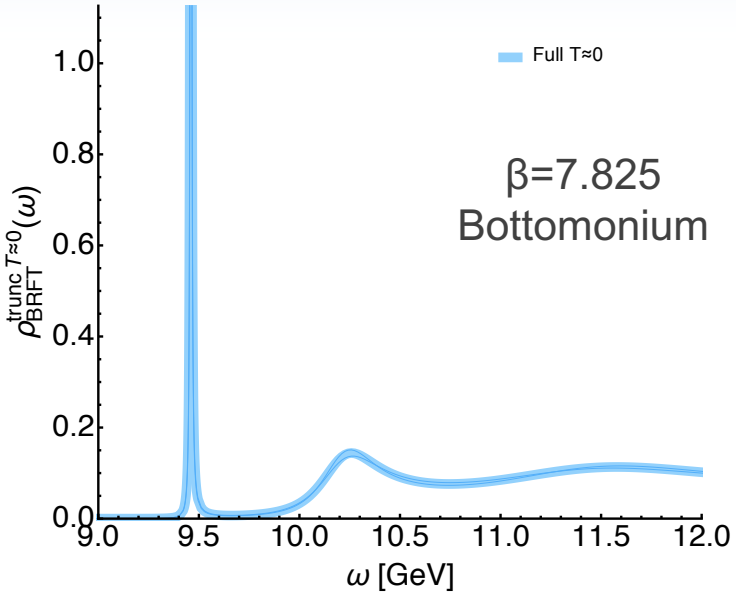

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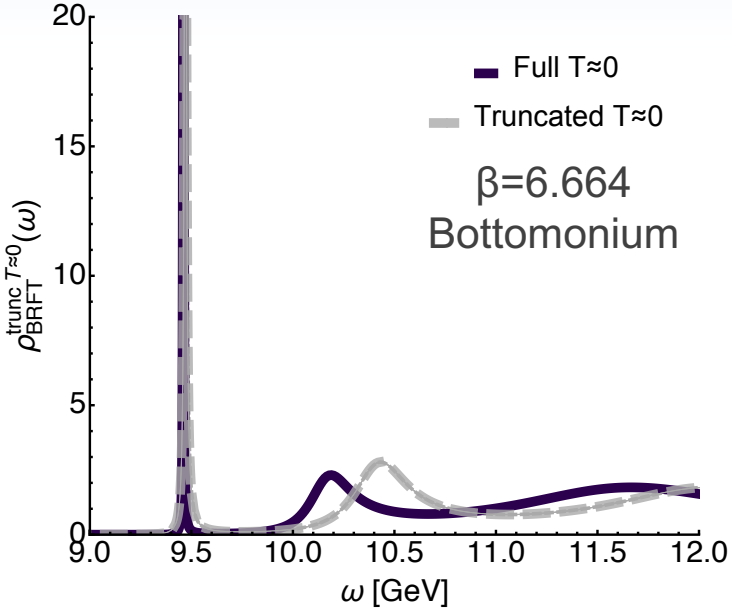
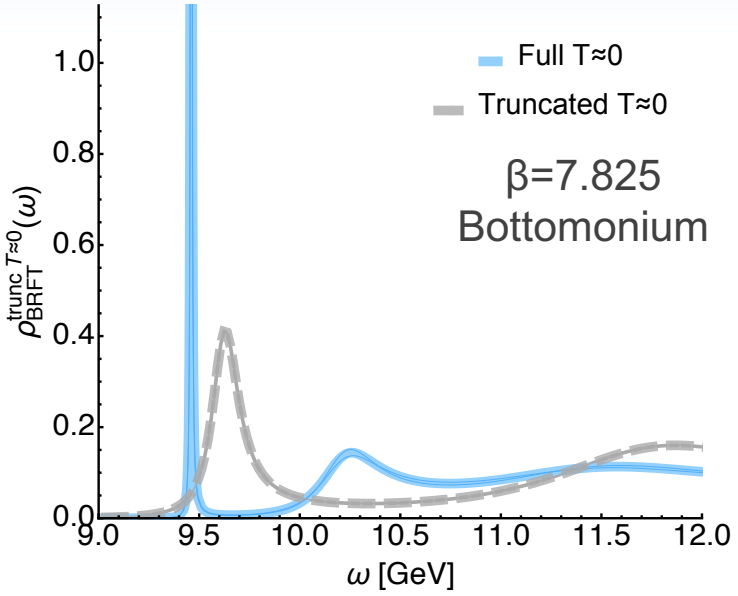
Taking control of systematics I

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





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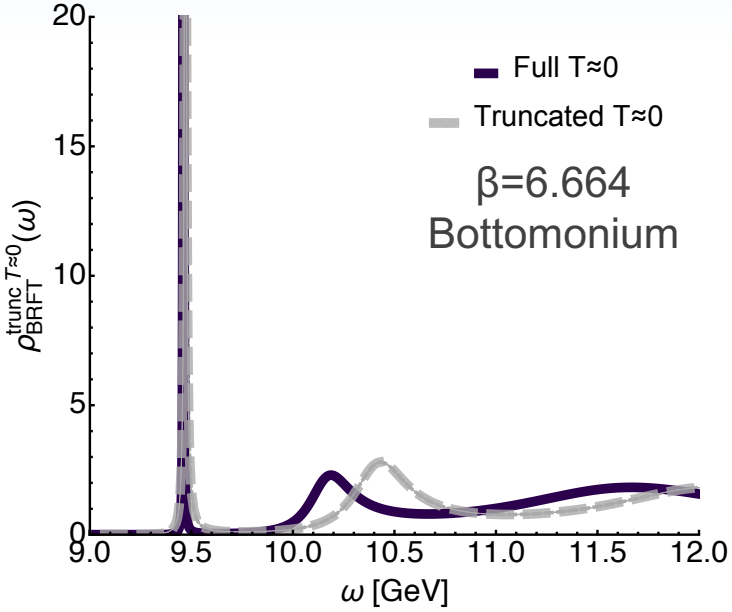

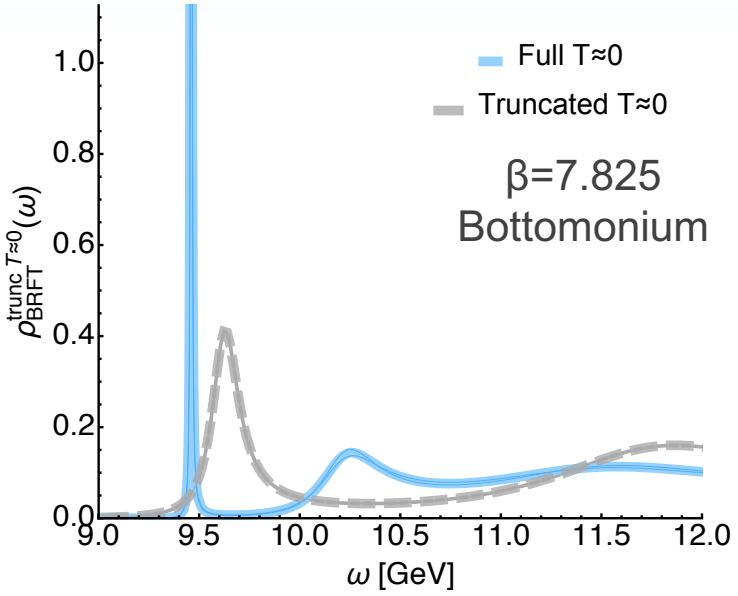

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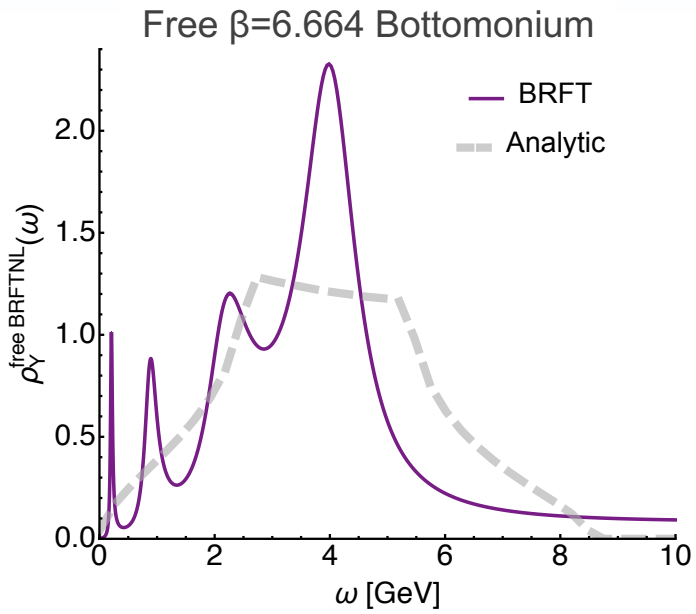
➡ Systematic shift of peaks to higher frequencies, as well as broadening. needs to be accounted for when analyzing T>0 spectra

Taking control of systematics II



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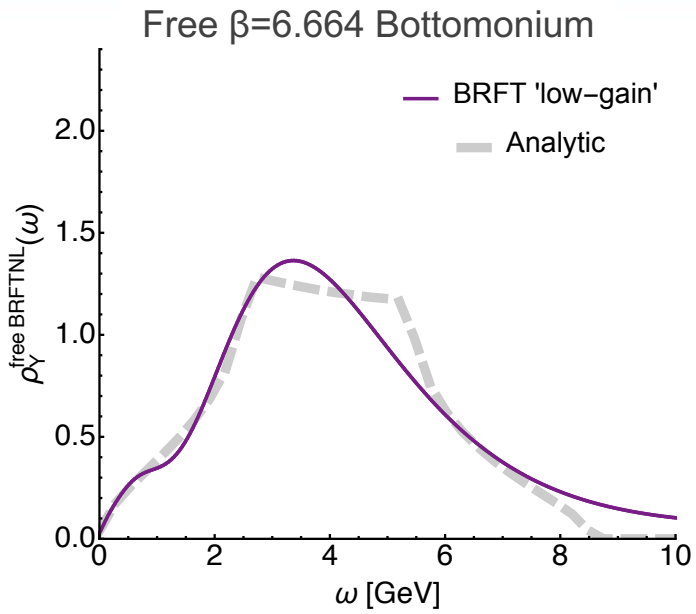

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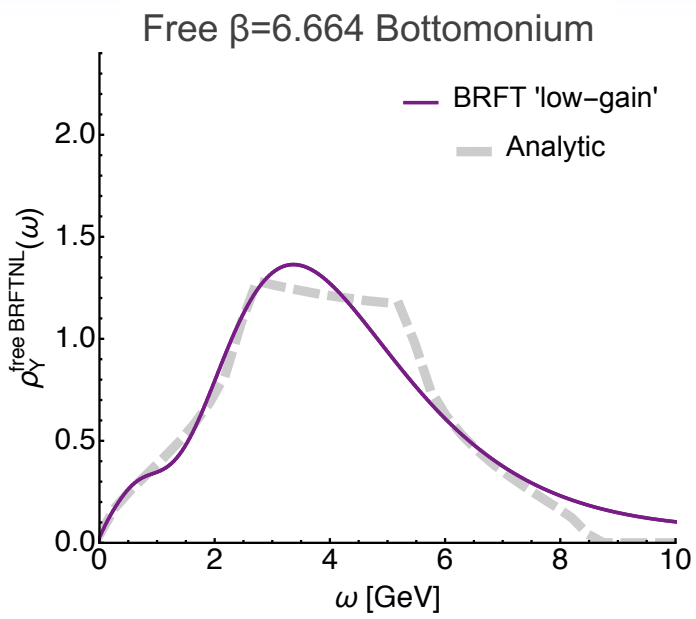

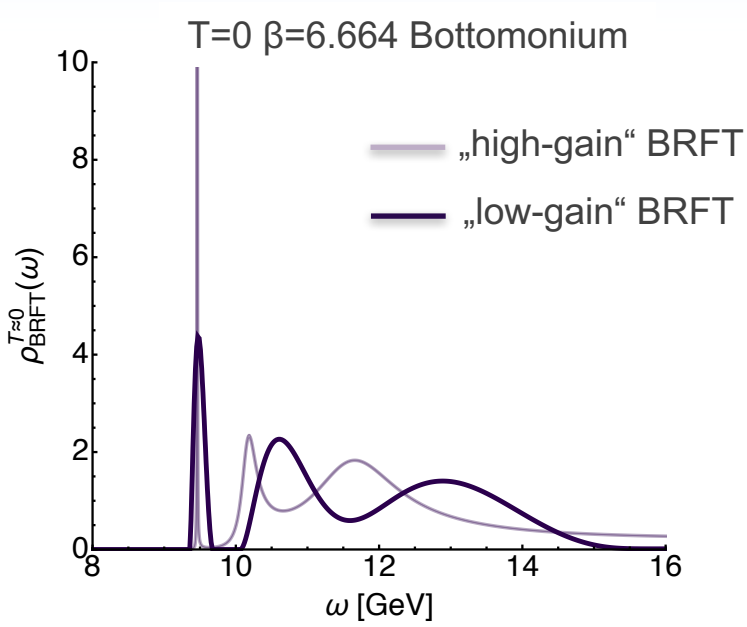

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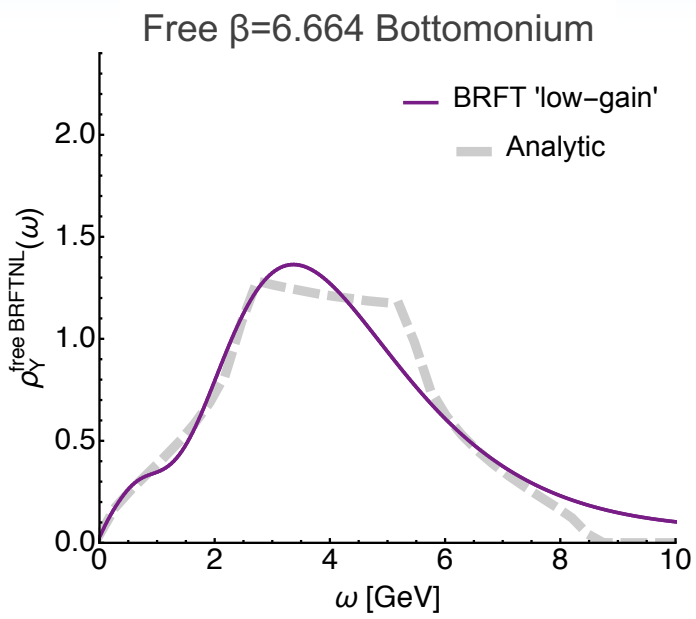

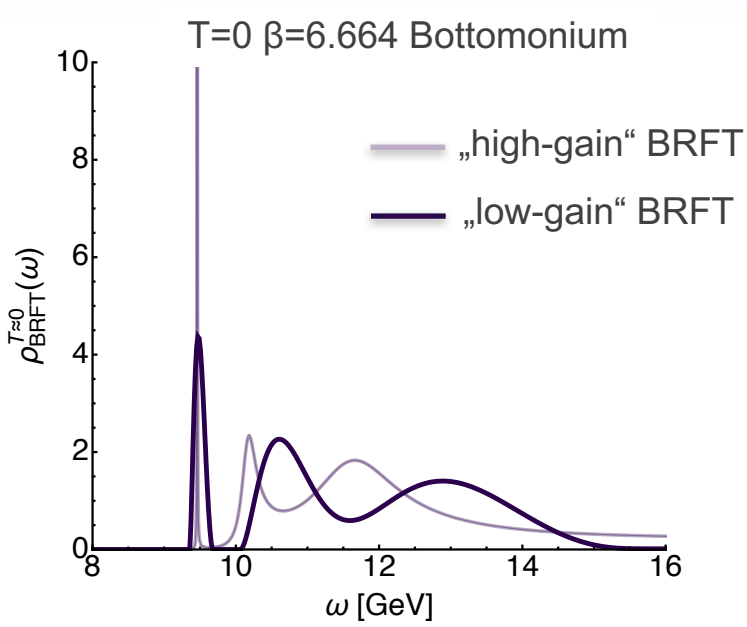

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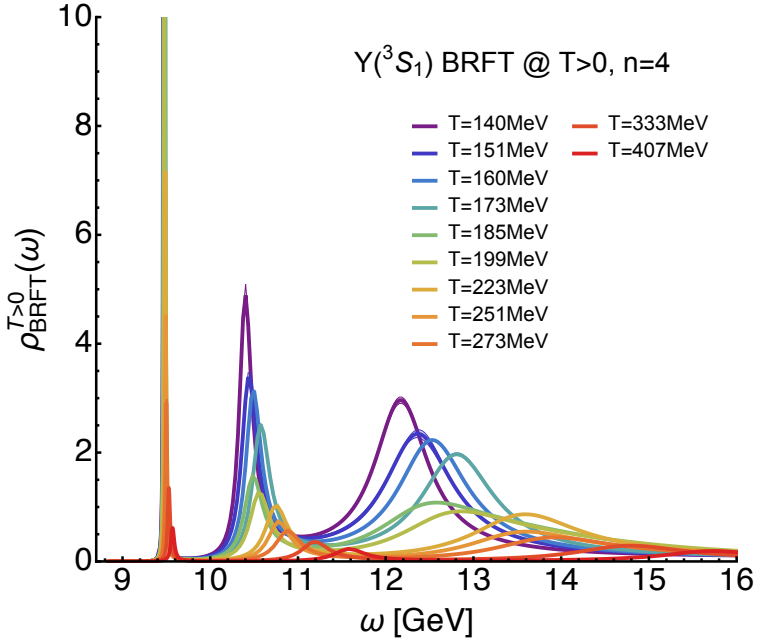
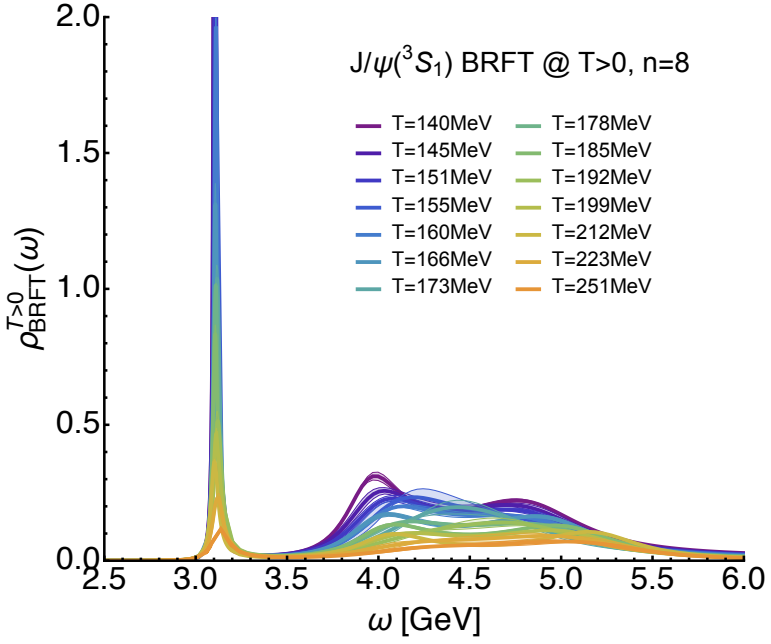
- Strategy: - Test with “low-gain” reconstruction whether peaks are genuine
  - Use “high-gain” reconstruction to extract peak features, e.g. position

Outline

- Motivation
  - Coherent picture of in-medium heavy-quarkonium from the lattice
- In-medium quarkonium from a lattice EFT (NRQCD)
  - Numerical setup and spectral reconstruction
  - Current T>0 results from realistic full QCD simulations
- Towards improved spectral information from thermal fields
  - Derivation of a novel simulation prescription
  - Current exploratory results from toy models to quenched QCD
- Conclusion

NRQCD S-wave spectra at T>0





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

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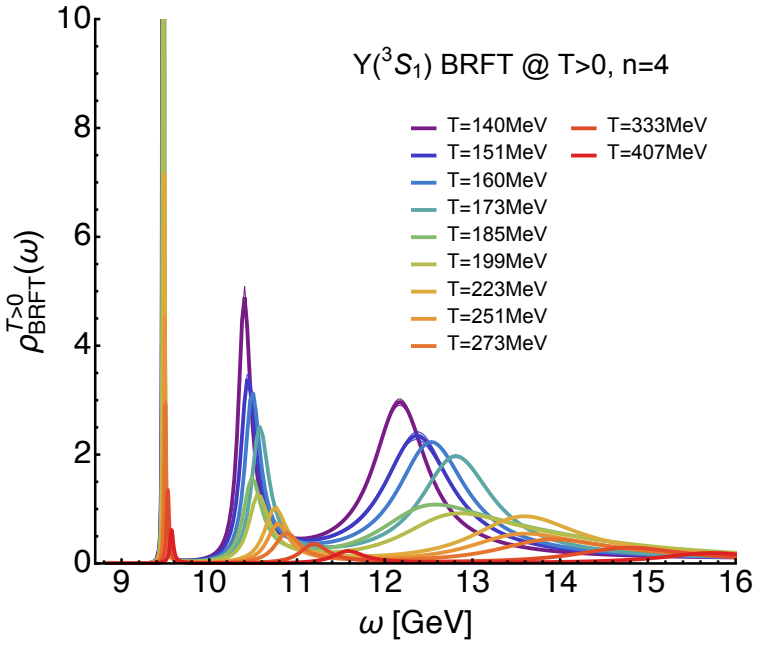

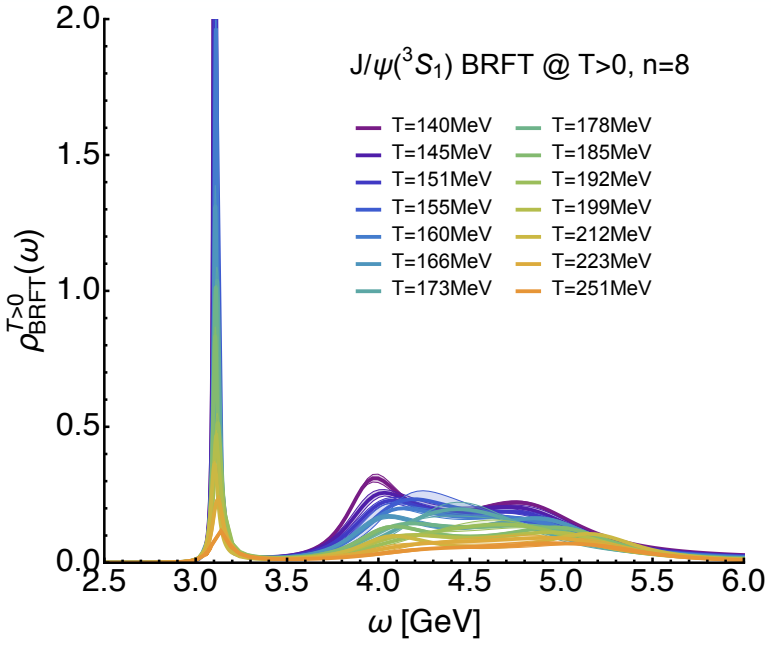

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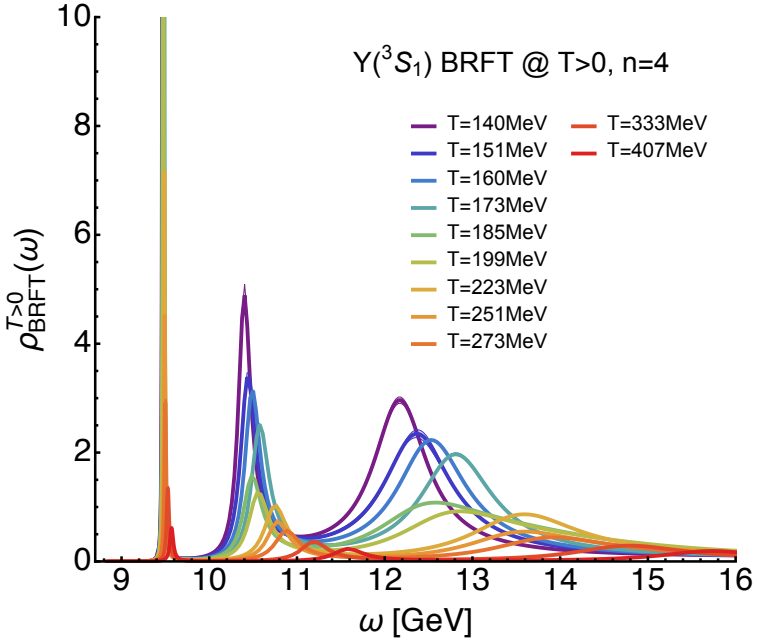

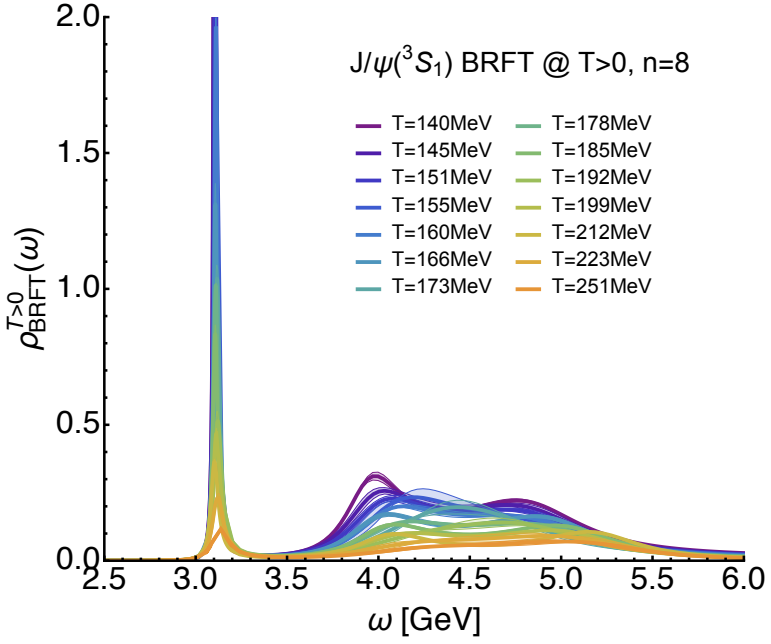

S.Kim, P.Petreczky, A.R. in preparation

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- Gradual broadening and shifting of lowest lying peak visible

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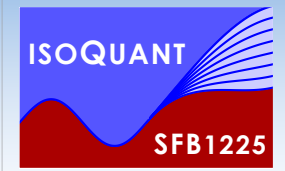

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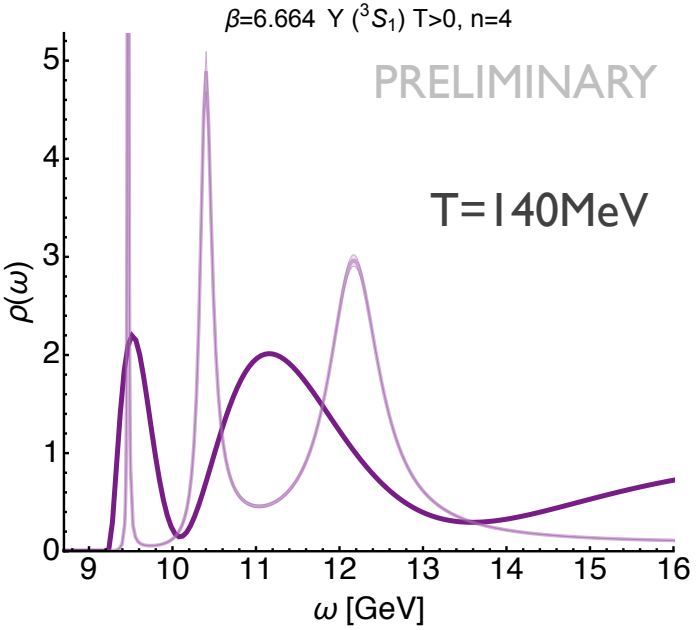

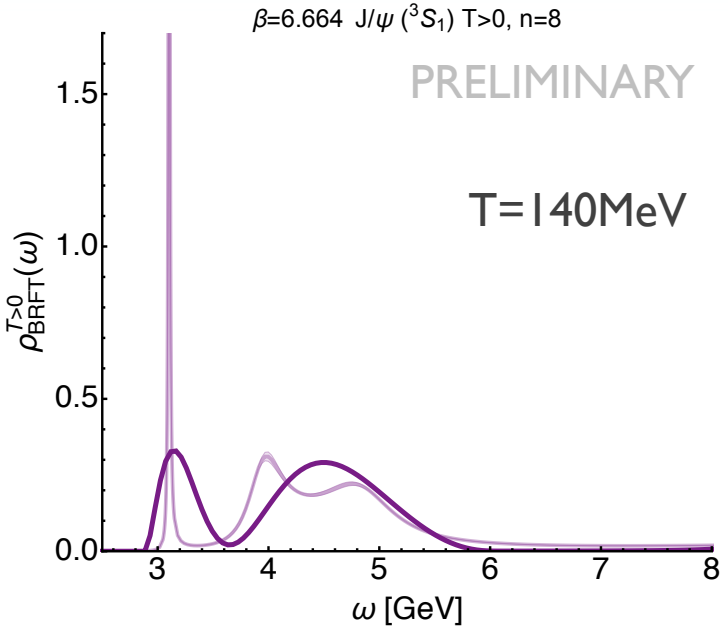

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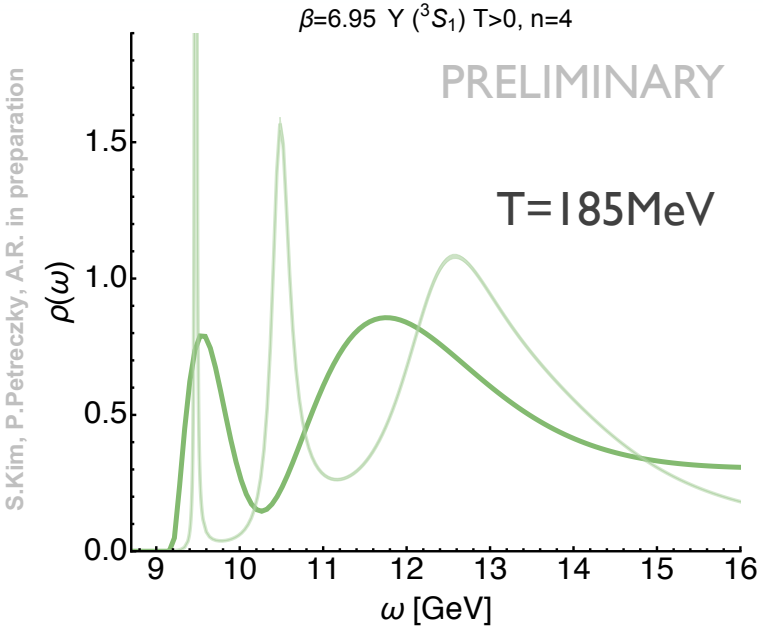

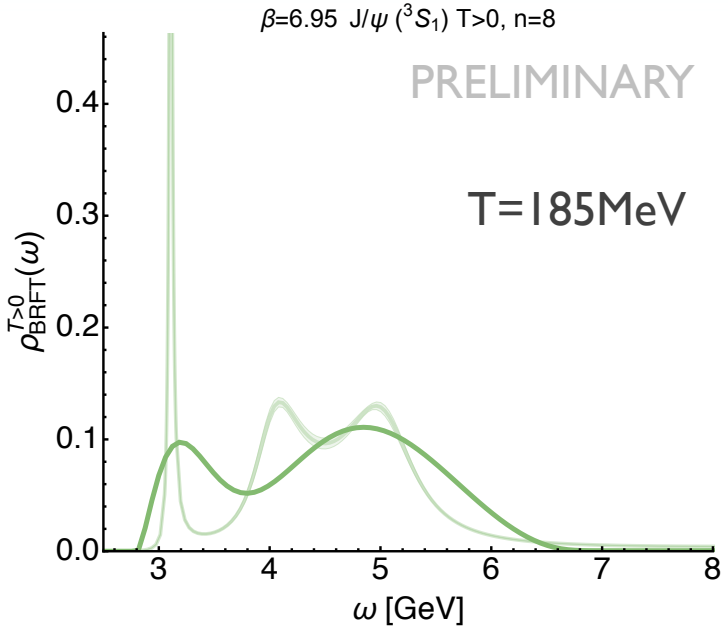

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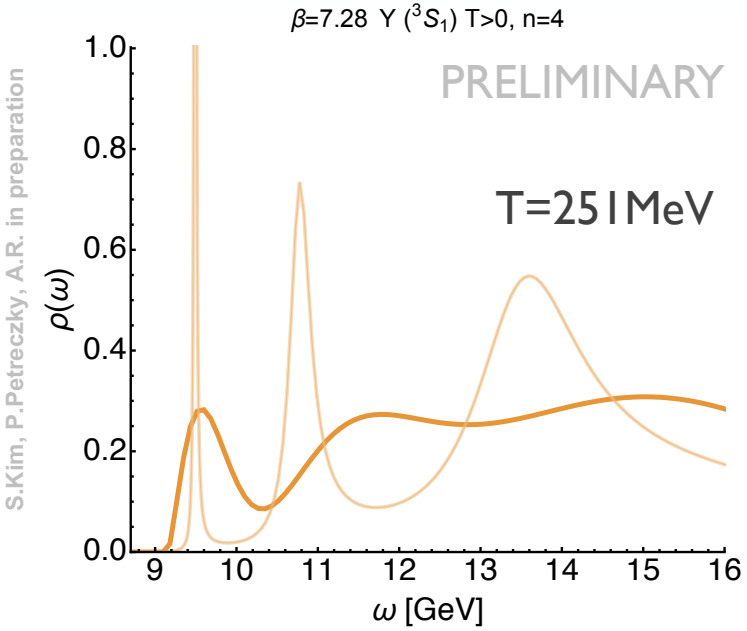

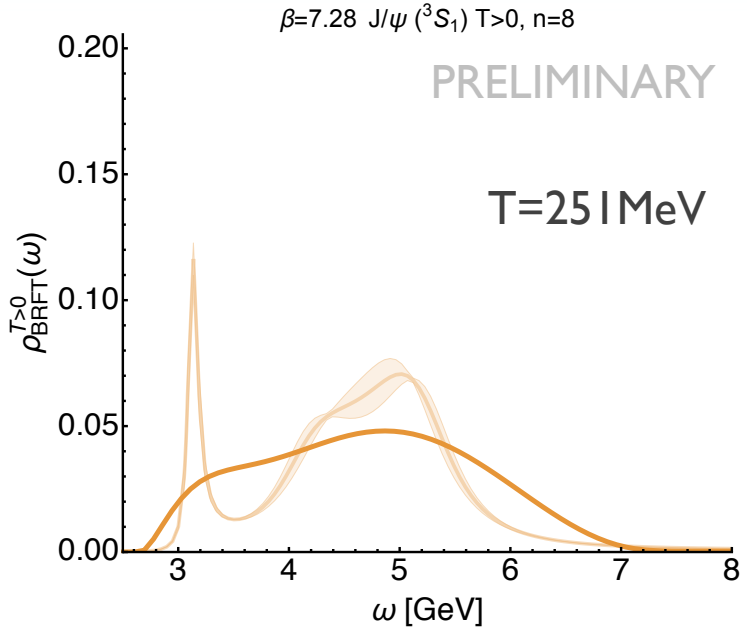

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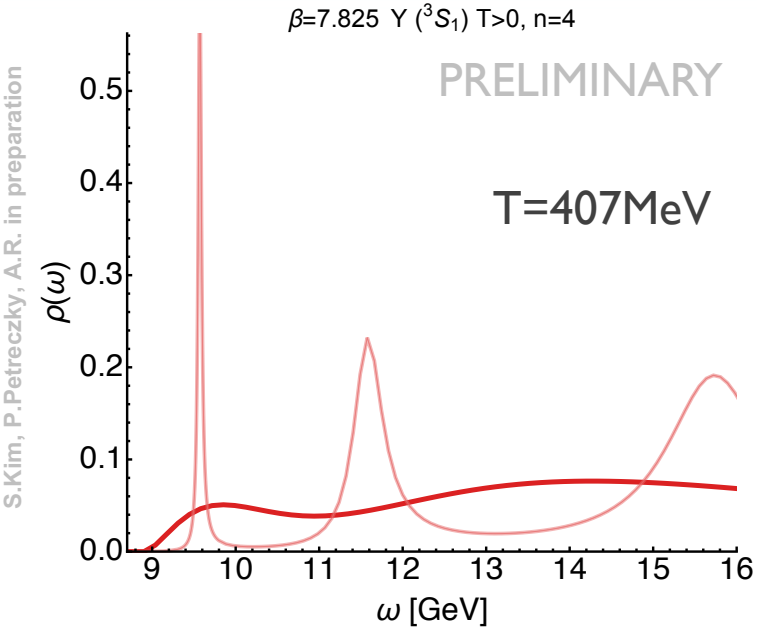

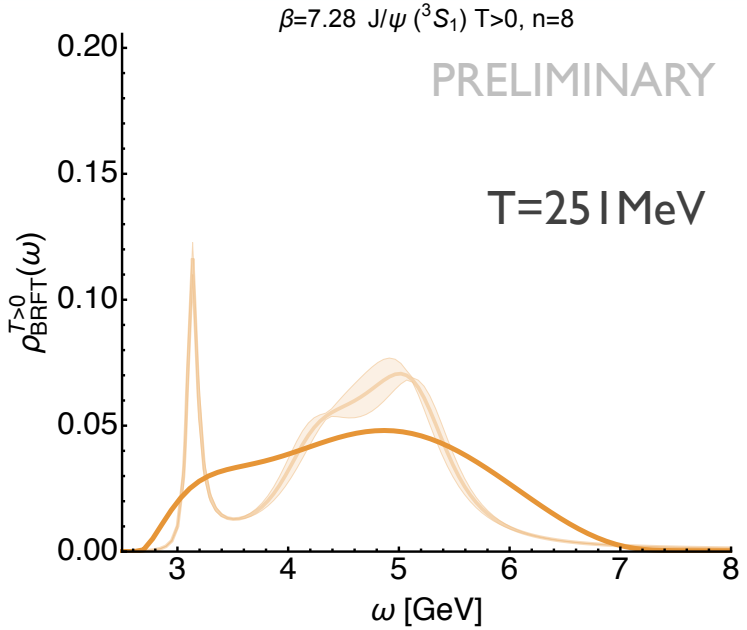

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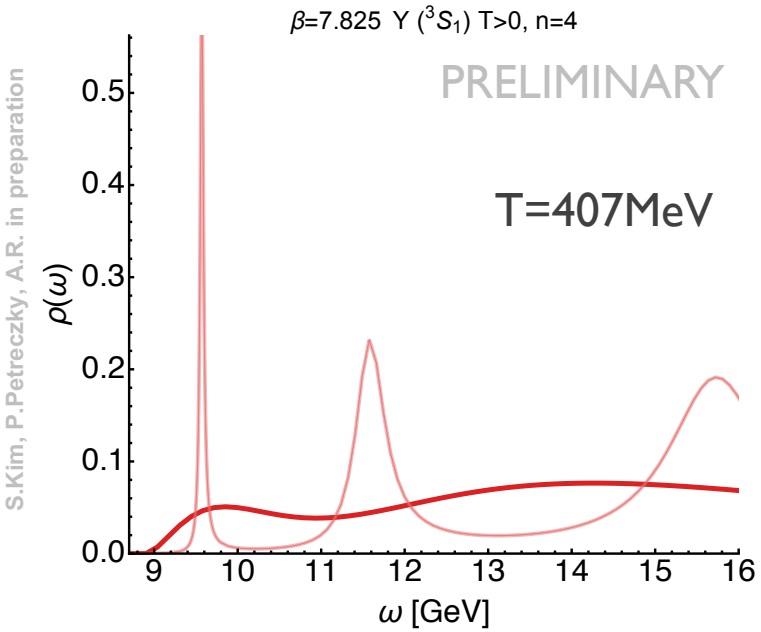

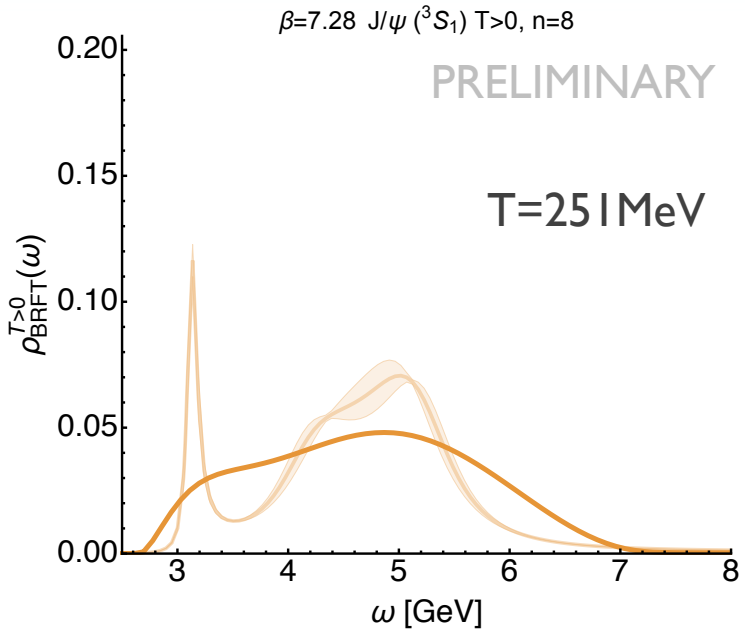

- New “low-gain” BR method shows gradual weakening of ground state signal

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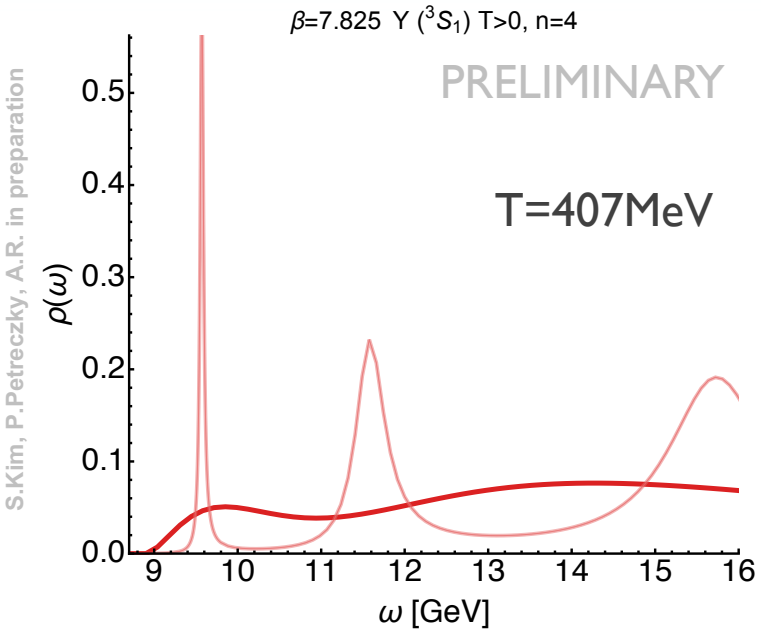
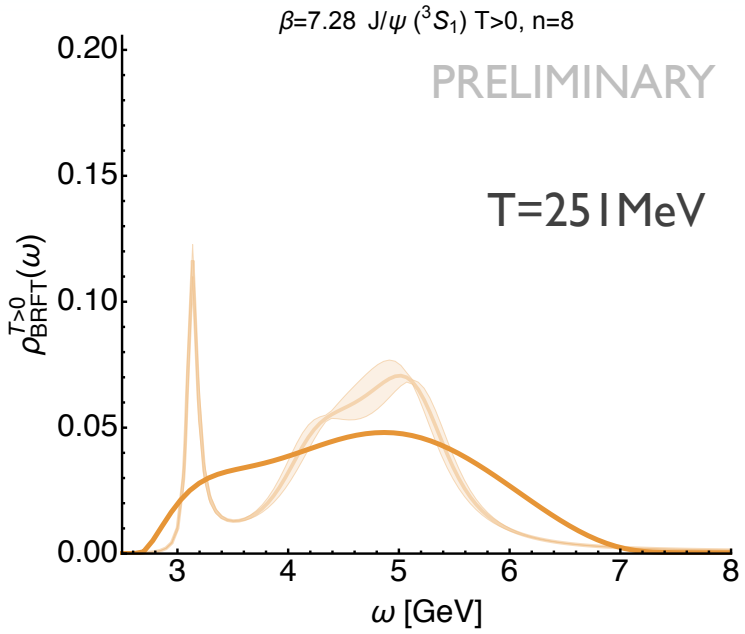


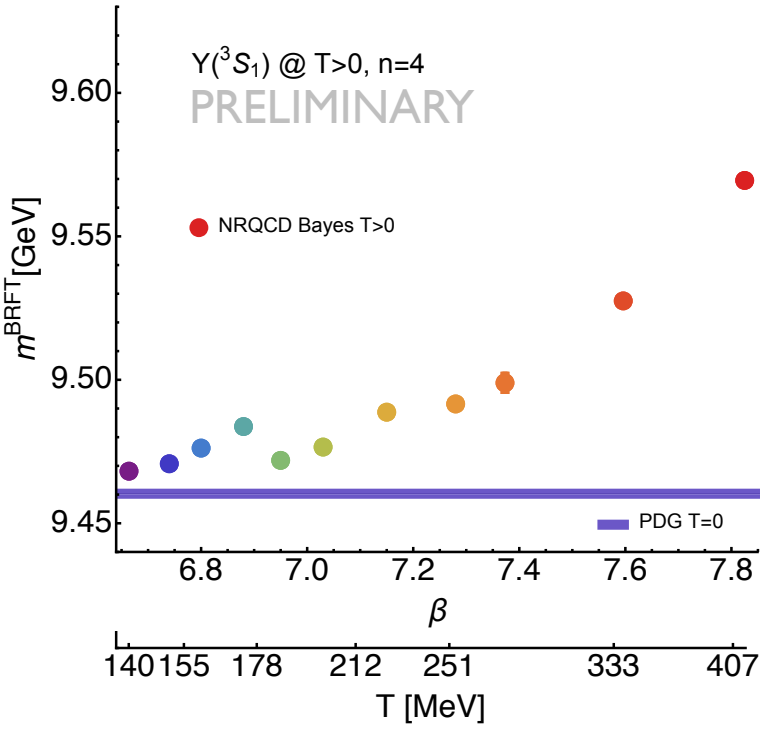


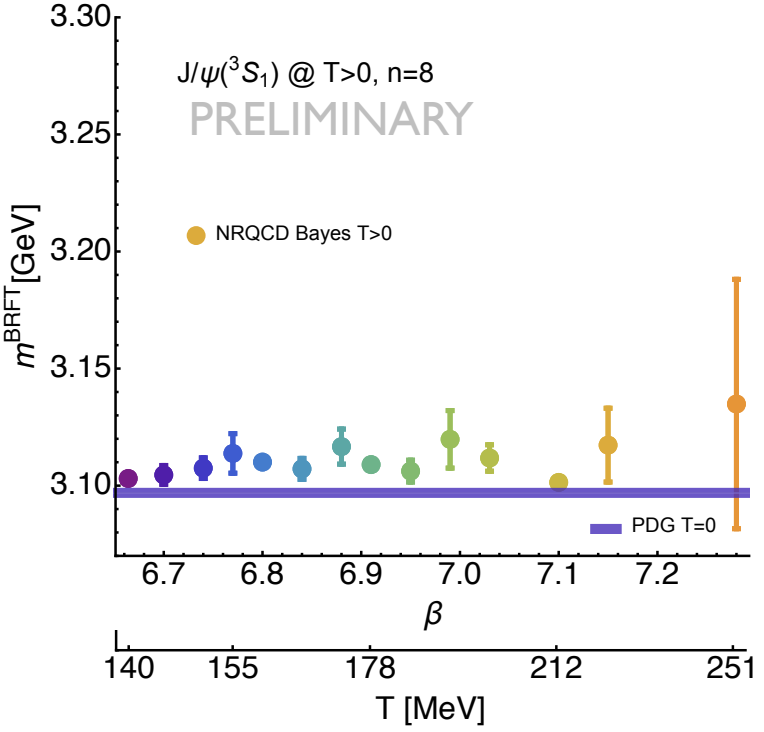
- New “low-gain” BR method shows gradual weakening of ground state signal
- At highest T in individual channels: weak ground state remnants remain visible

Upsilon signal up to T=407MeV

Faint J/ψ signal up to T=251MeV

In-medium S-wave mass shifts





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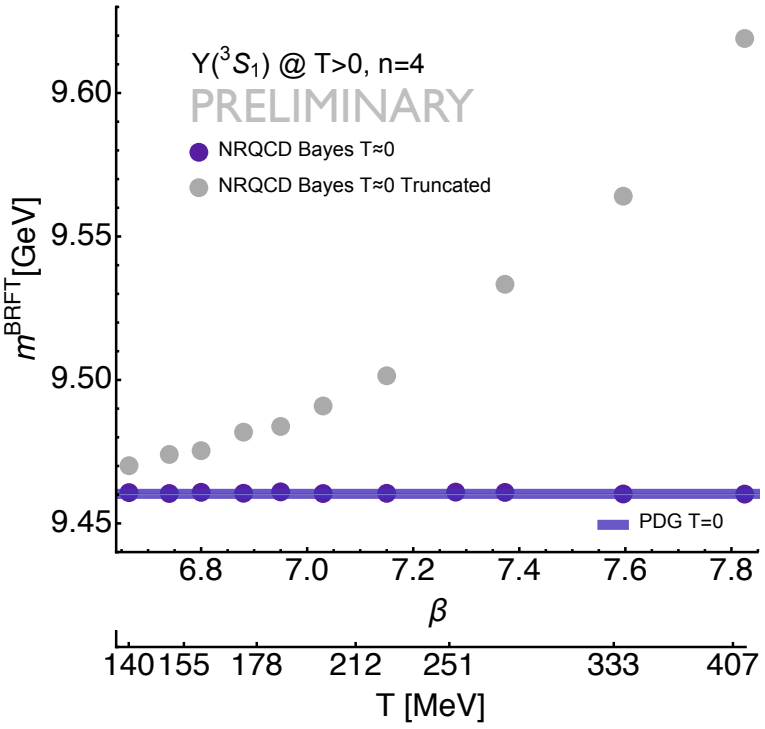

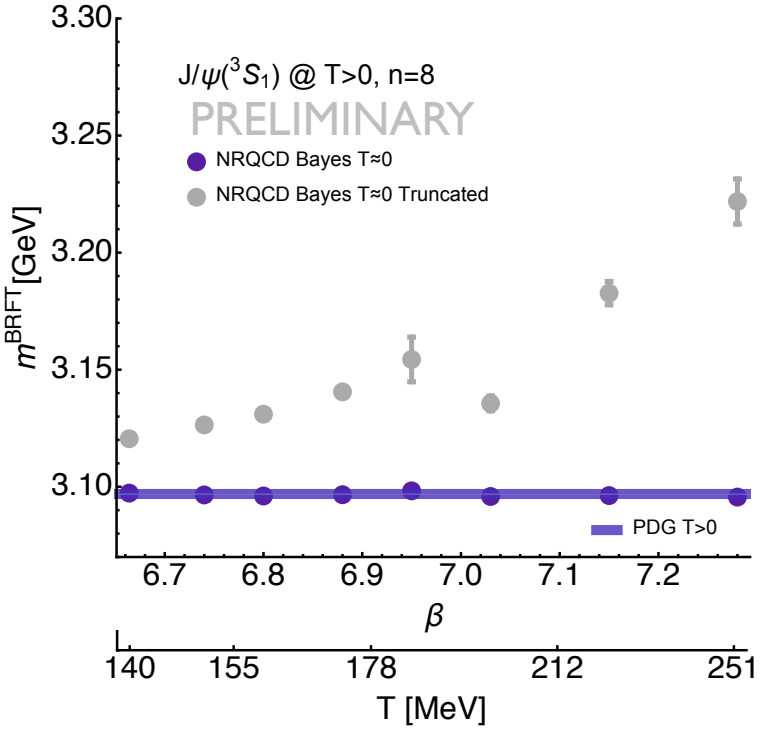

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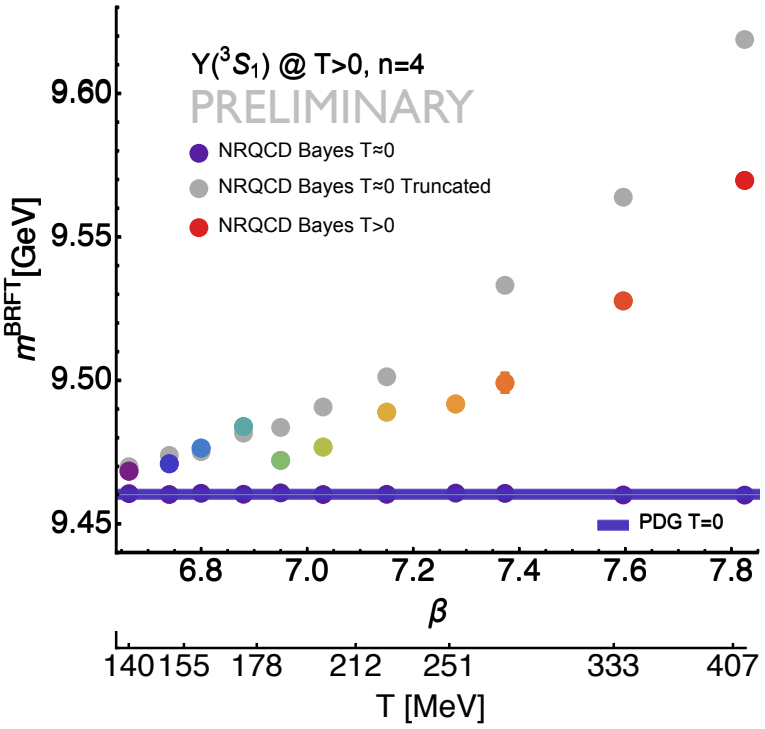

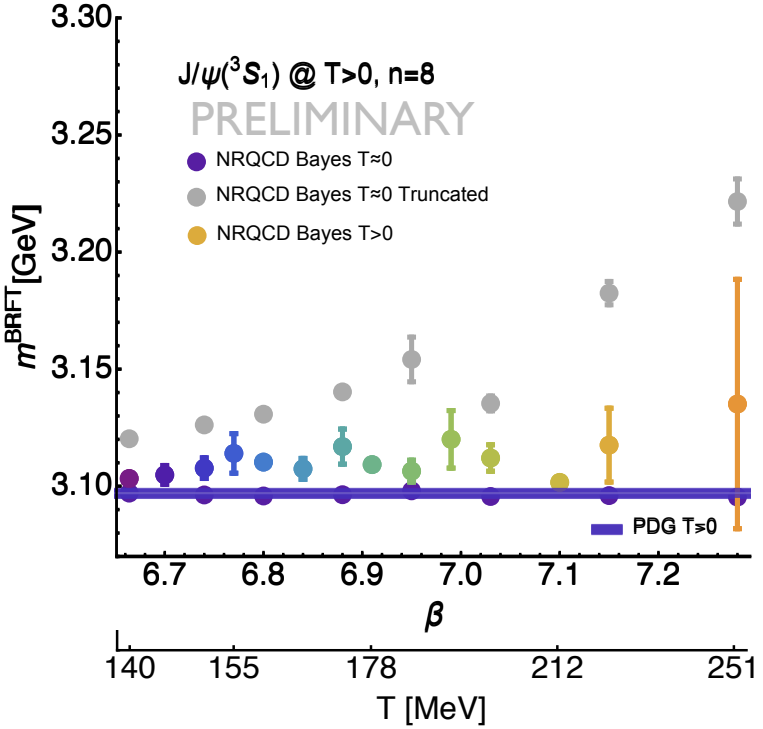

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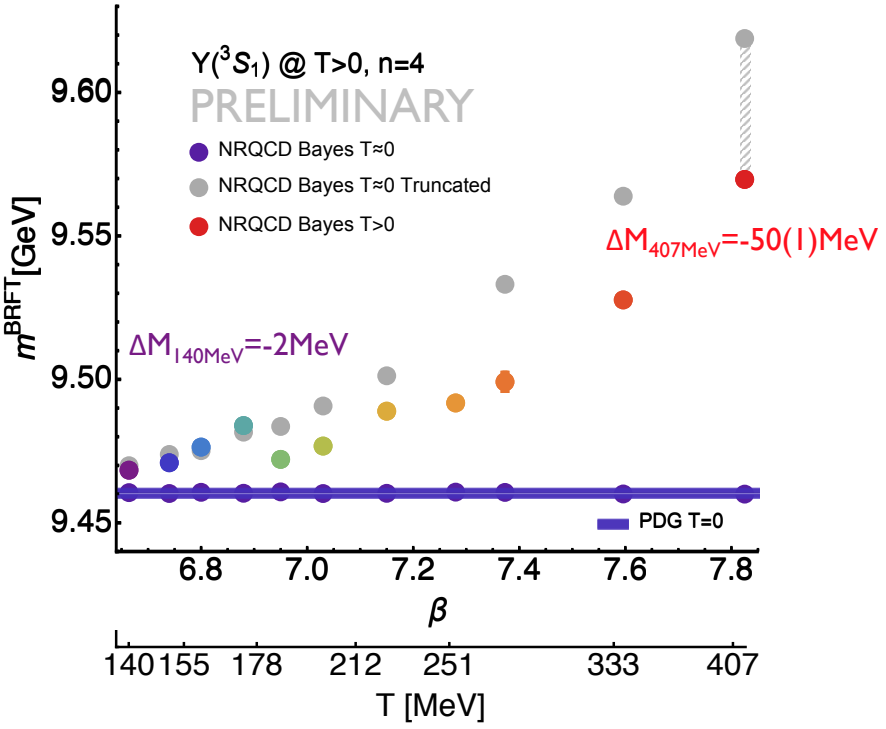

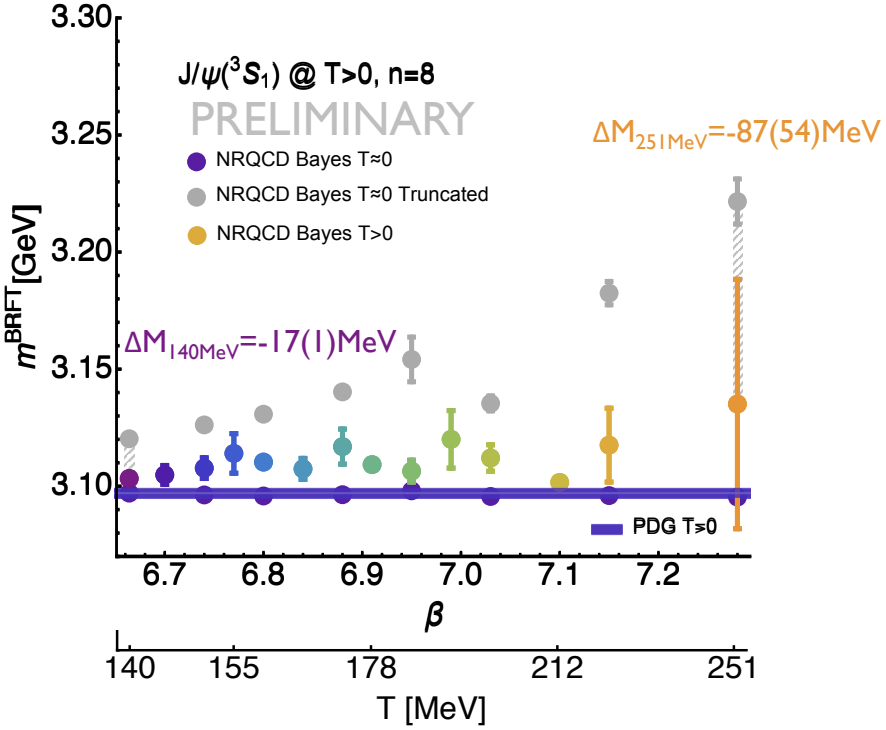

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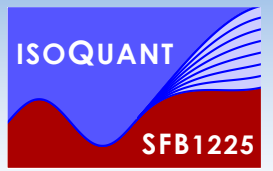
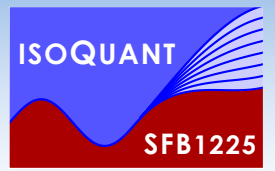
- Actual in-medium effect: lowering of bound state mass, consistent with potential studies



Outline

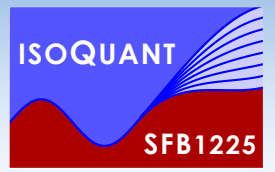
- Motivation
  - Coherent picture of in-medium heavy-quarkonium from the lattice
- In-medium quarkonium from a lattice EFT (NRQCD)
  - Numerical setup and spectral reconstruction
  - Current T>0 results from realistic full QCD simulations
- Towards improved spectral information from thermal fields
  - Derivation of a novel simulation prescription
  - Current exploratory results from toy models to quenched QCD
- Conclusion



The underlying difficulty

- Intrinsic problem of standard spectral reconstruction: exponential information loss

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



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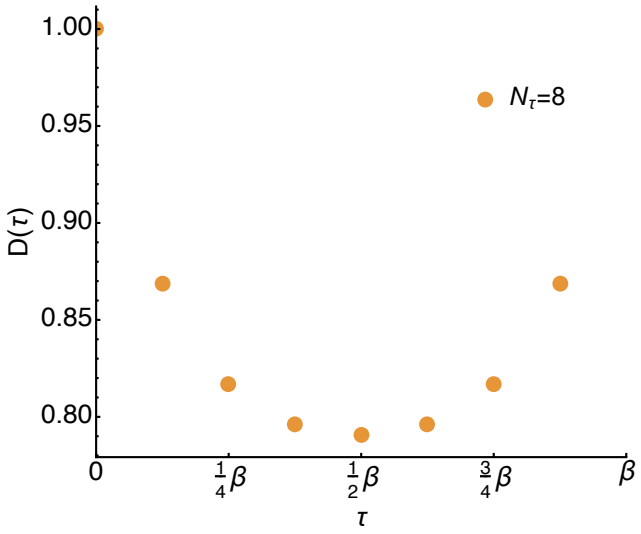

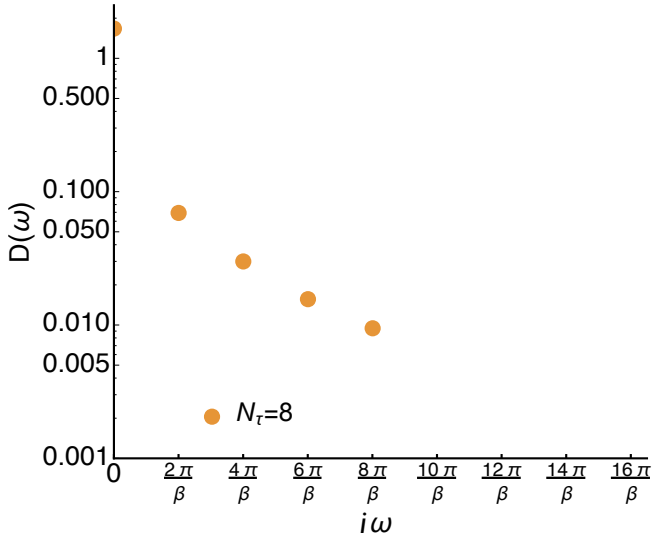

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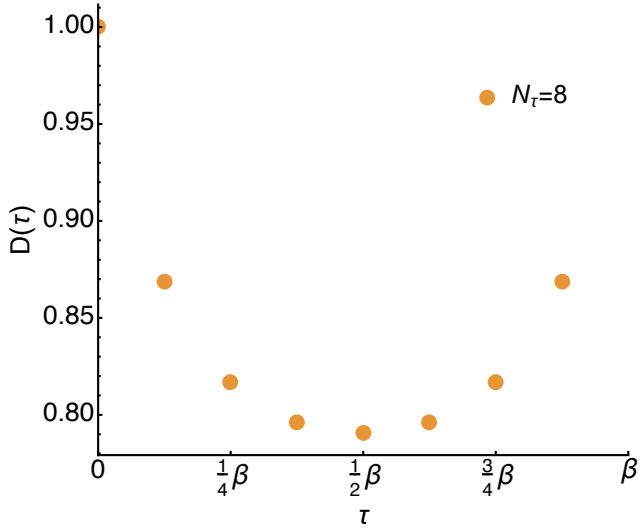

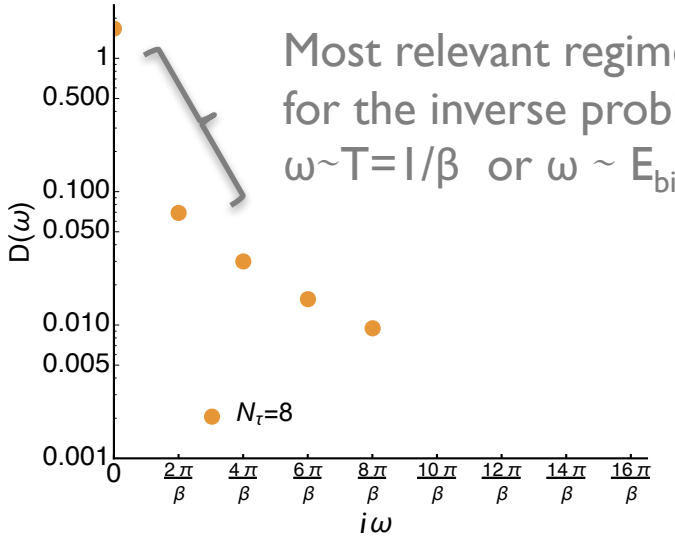

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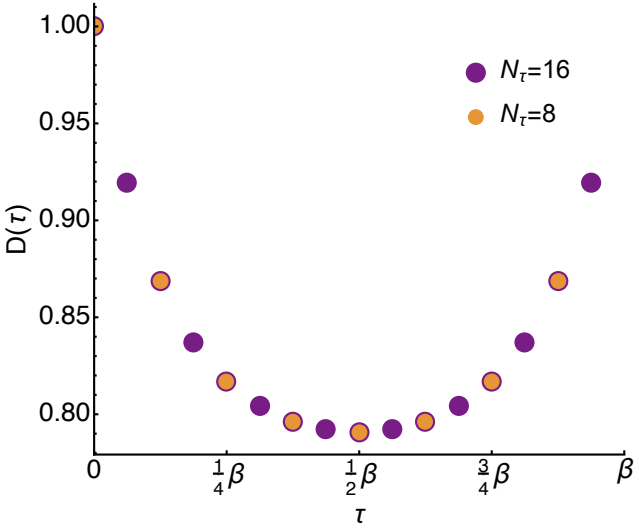

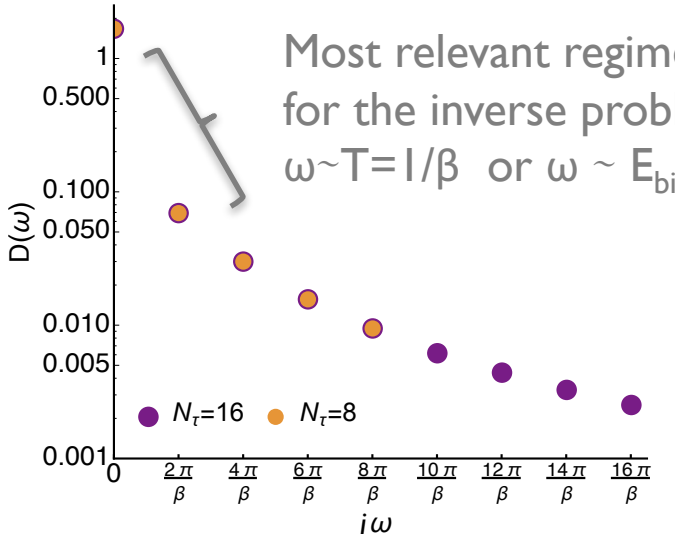

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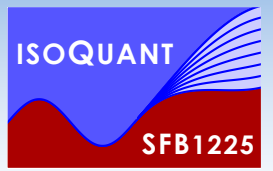

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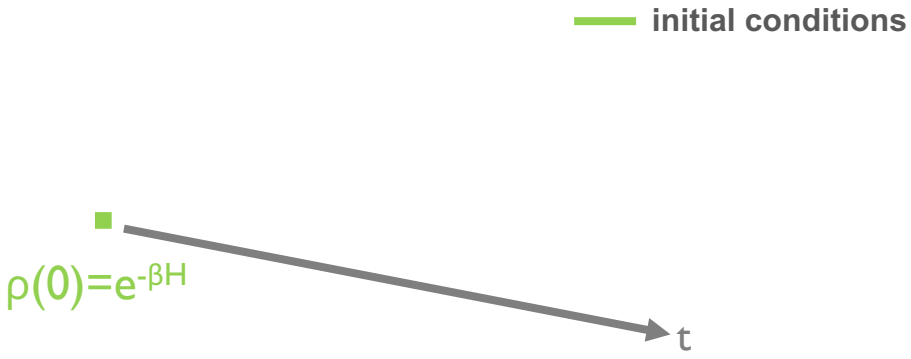

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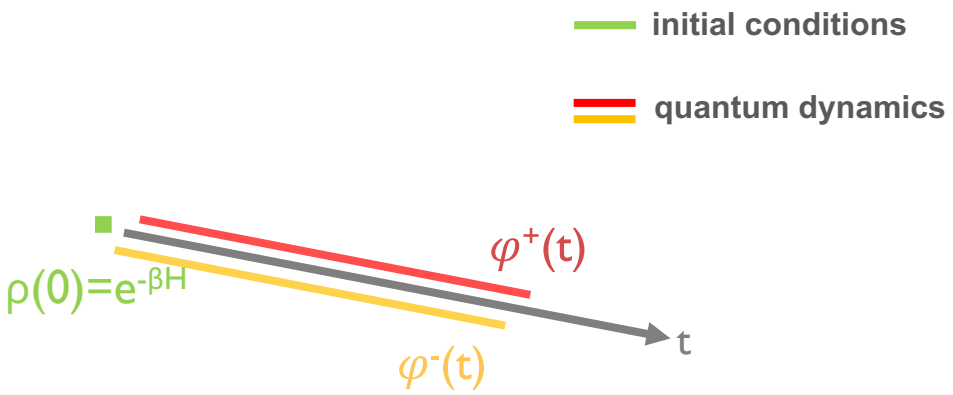

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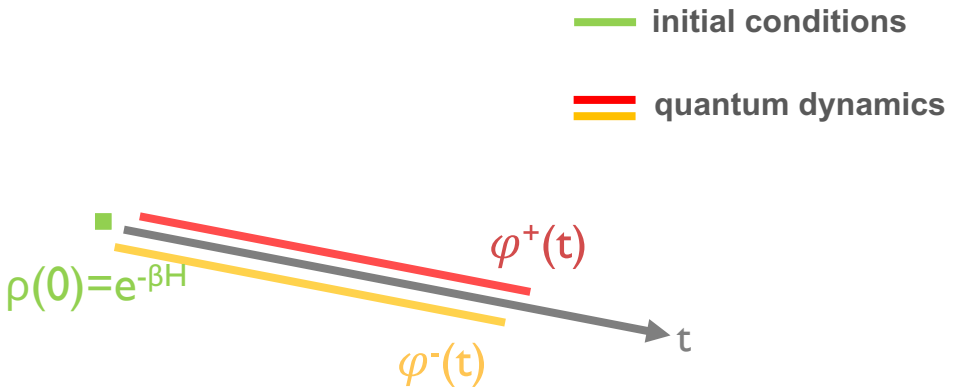

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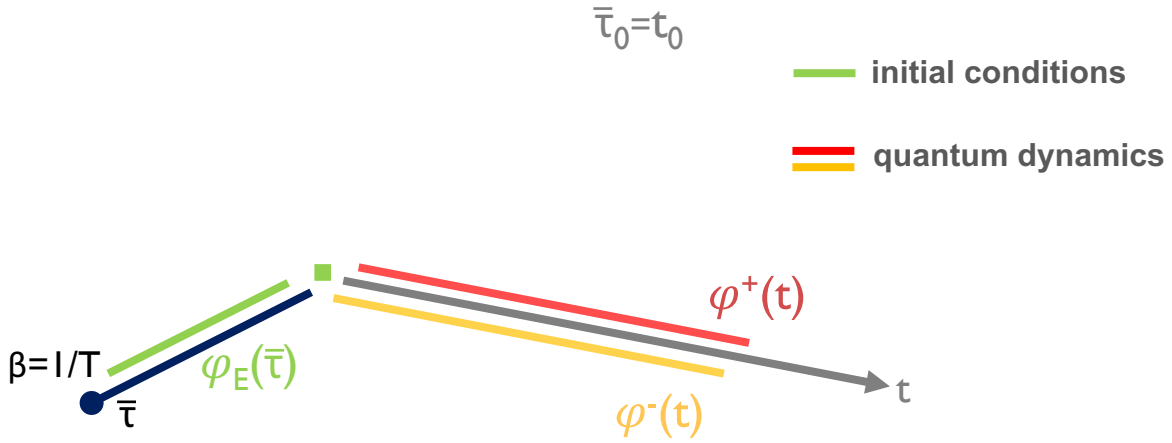

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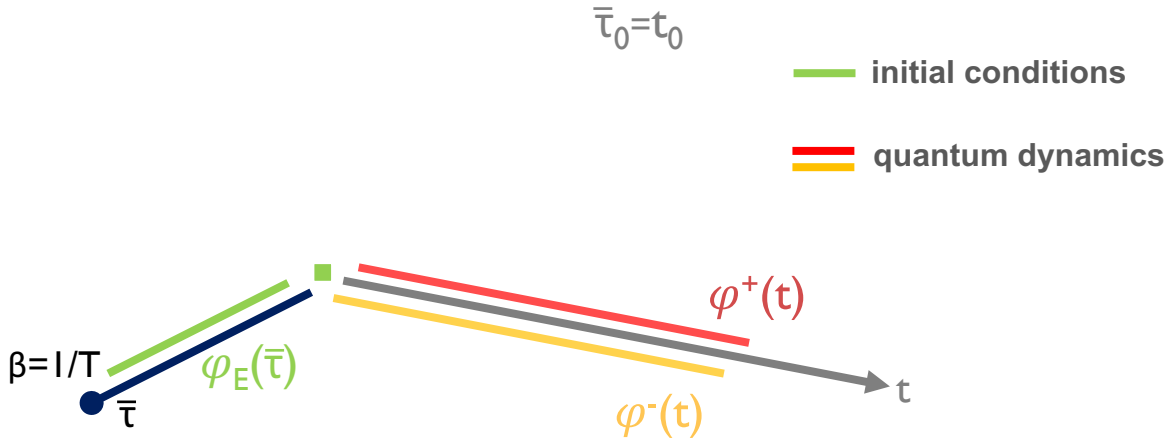
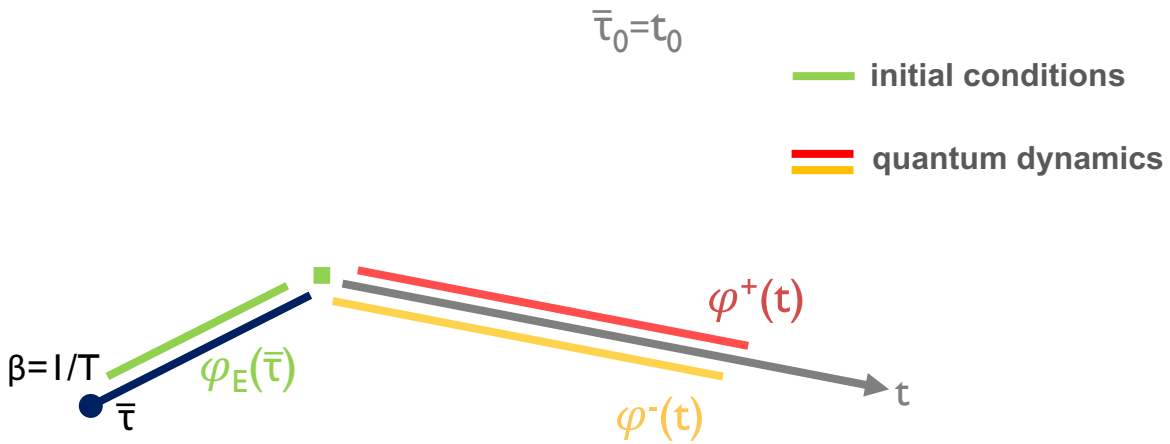


- At this stage: Euclidean time as a mathematical tool to sample $\varphi^+(t_0)$ and $\varphi^-(t_0)$

How do the two paths contribute?

- Thermal equilibrium is special: $G^{++}=\langle\varphi^{+}\varphi^{+}\rangle$ correlator alone suffices to compute ρ

$$G^{++}(p^0,\mathbf{p}) = \int \frac{dq^0}{2\pi i}\frac{\rho(q^0,\mathbf{p})}{p^0 - q^0 + i\epsilon} - n(p^0)\rho(p^0,\mathbf{p})$$



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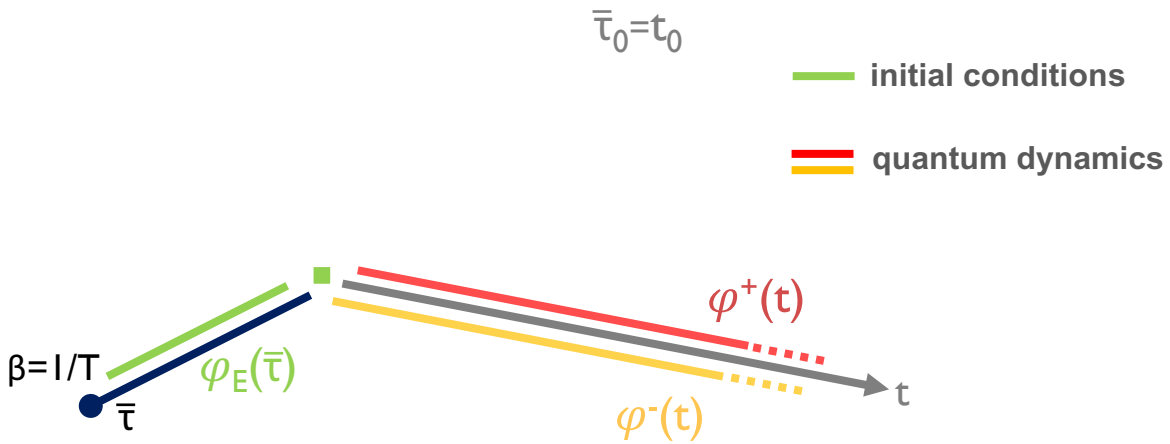
- In thermal equilibrium: time translational invariance $t_0 \to -\infty$



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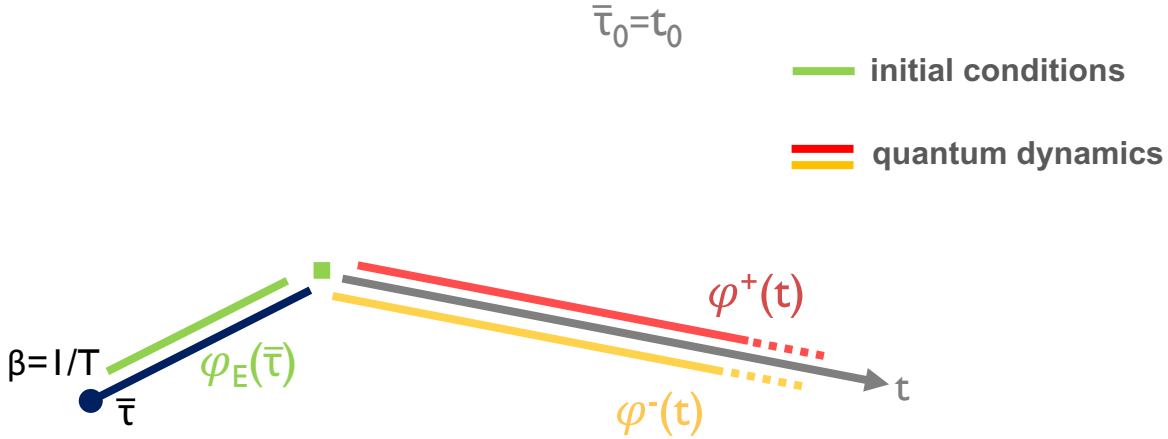

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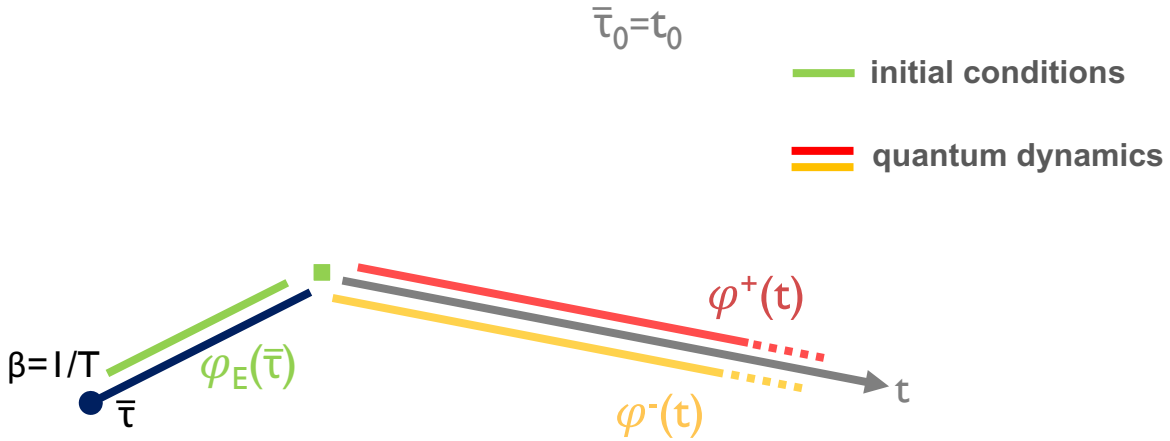
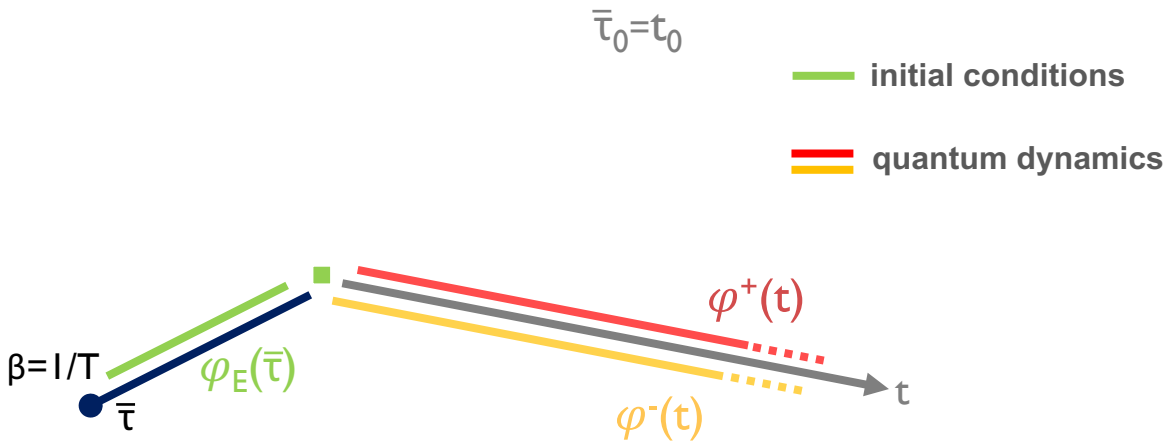


- Focus on treating the forward branch with φ+ in the following

Analytic continuation

- Our idea: rotate branches of the real-time contour into noncompact imaginary time

$$\mathcal{Z} = \int_{\varphi_E(0)=\varphi_E(\beta)} \mathcal{D}\varphi_E e^{-S_E[\varphi_E]} \int_{\varphi^+(t_0,\mathbf{x})=\varphi_E(0)}^{\varphi^-(t_0,\mathbf{x})=\varphi_E(\beta)} \mathcal{D}\varphi e^{iS_M[\varphi^+]-iS_M[\varphi^-]}$$



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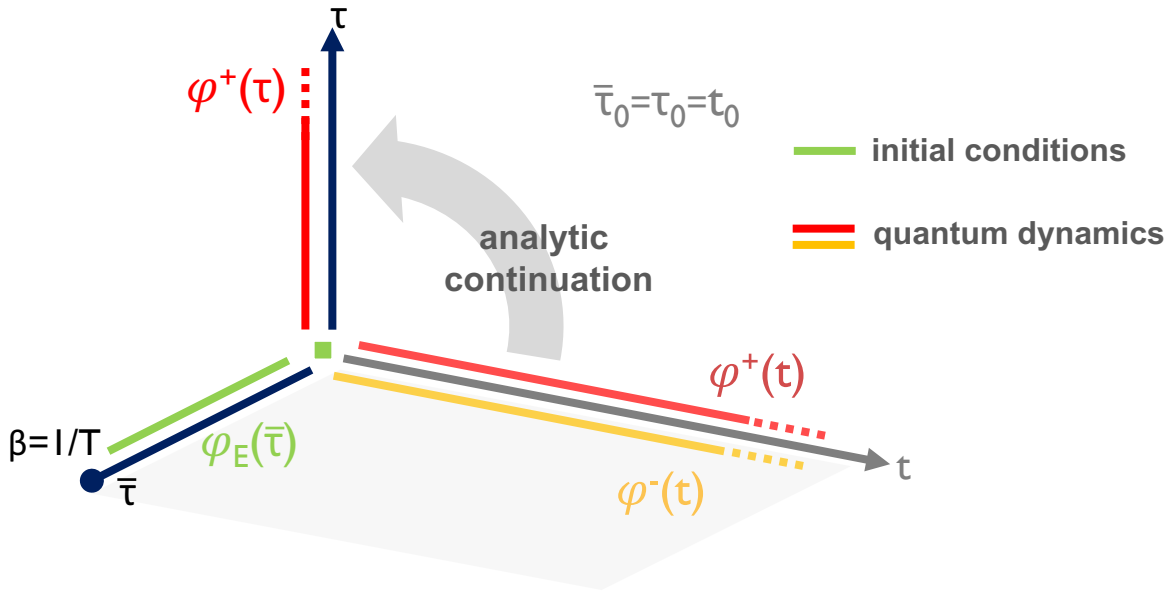

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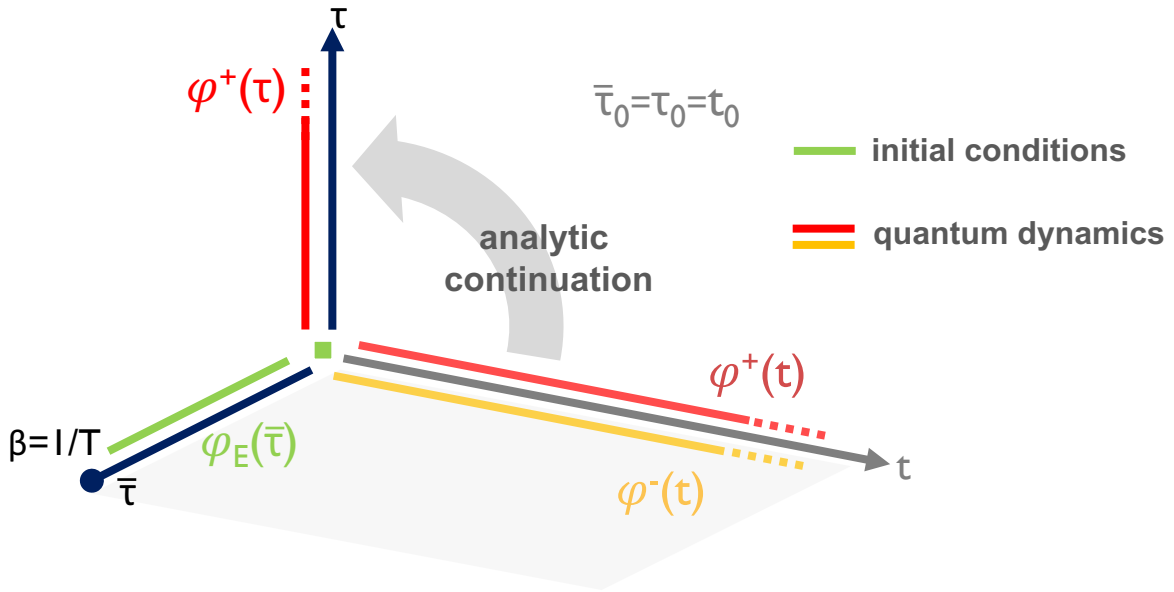

- After analytic continuation ρ from G++: $G^{++}(ip^0,\mathbf{p}) = \int \frac{dq^0}{2\pi} \frac{\rho(q^0,\mathbf{p})}{ip^0 - q^0} - n(p^0) \underbrace{\rho(ip^0,\mathbf{p})}_{=0}$

Simulating φ^+ in (0+1) dimensions

- Combine standard simulation of $\varphi_E(\bar{\tau})$ with additional simulation of $\varphi^+(\tau)$

$$S_E = \int d\tau \Big(\underbrace{\frac{1}{2}(\partial_\tau \varphi_E)^2 + \frac{1}{2} m^2 \varphi_E^2}_{S_E^0} + \underbrace{\frac{\lambda}{4!}\varphi_E^4}_{S_E^{int}} \Big)$$

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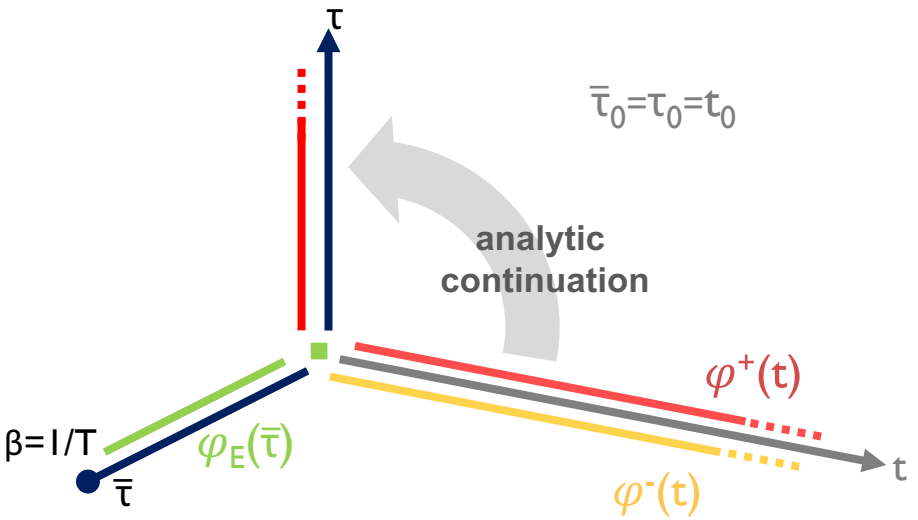

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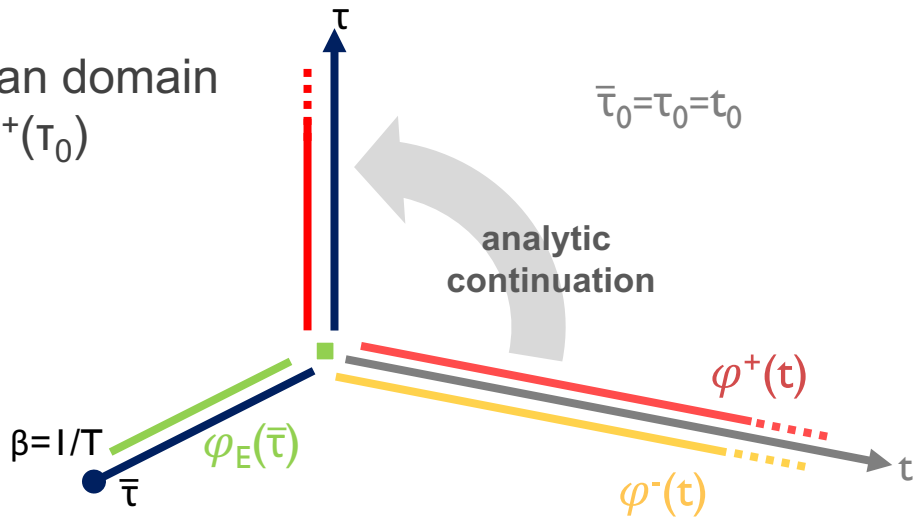

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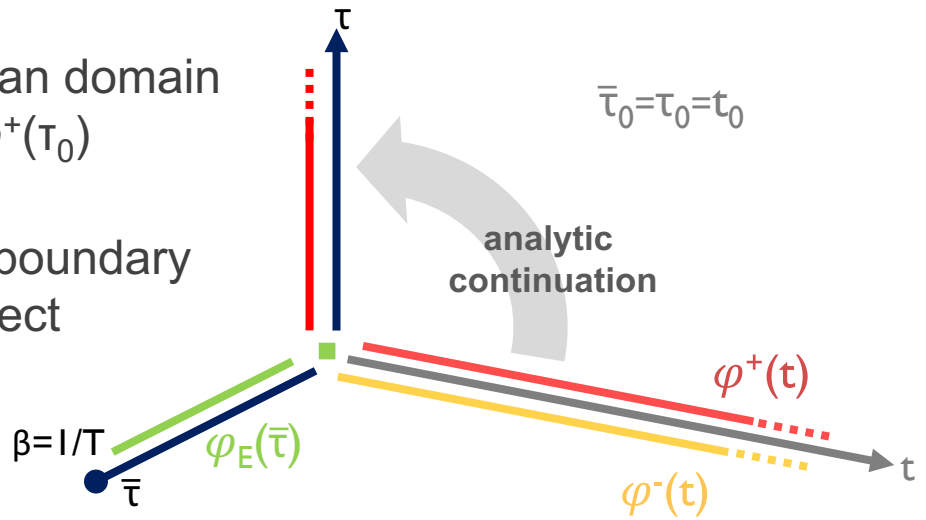

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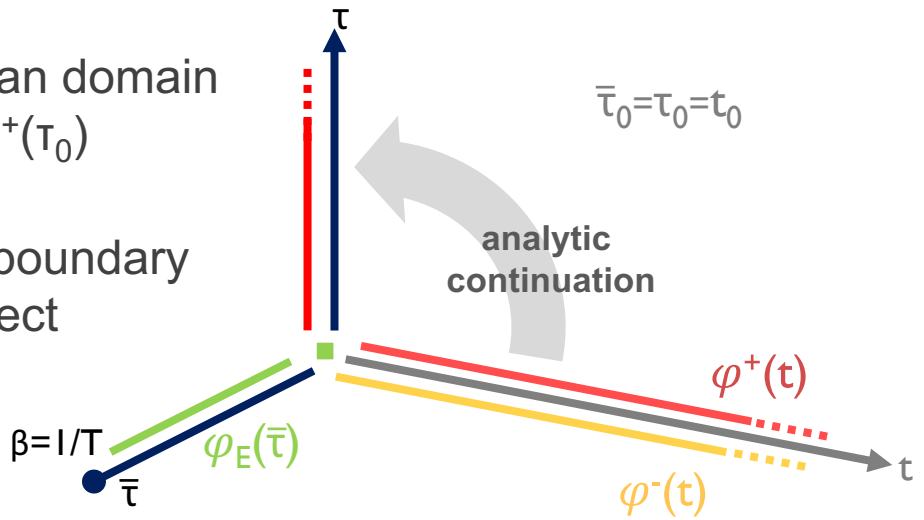

Forier space implementation

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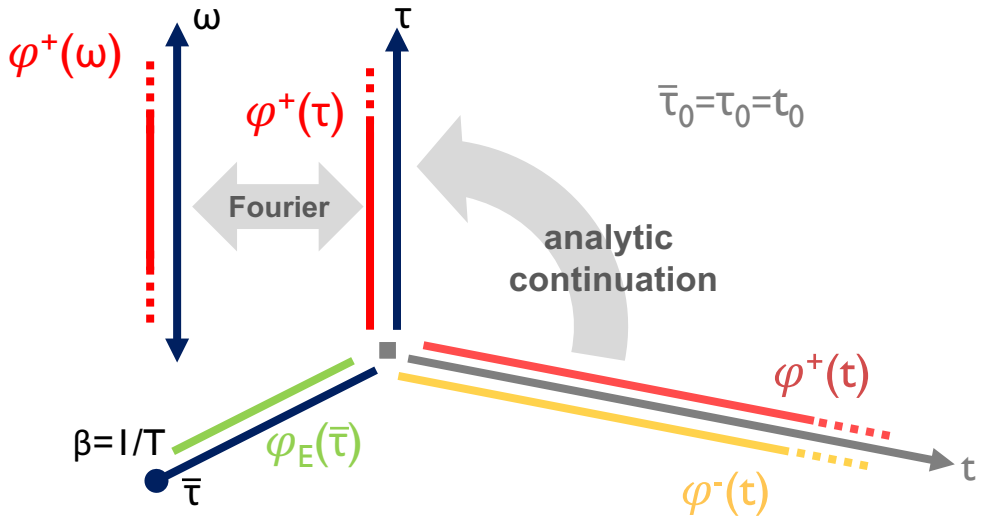

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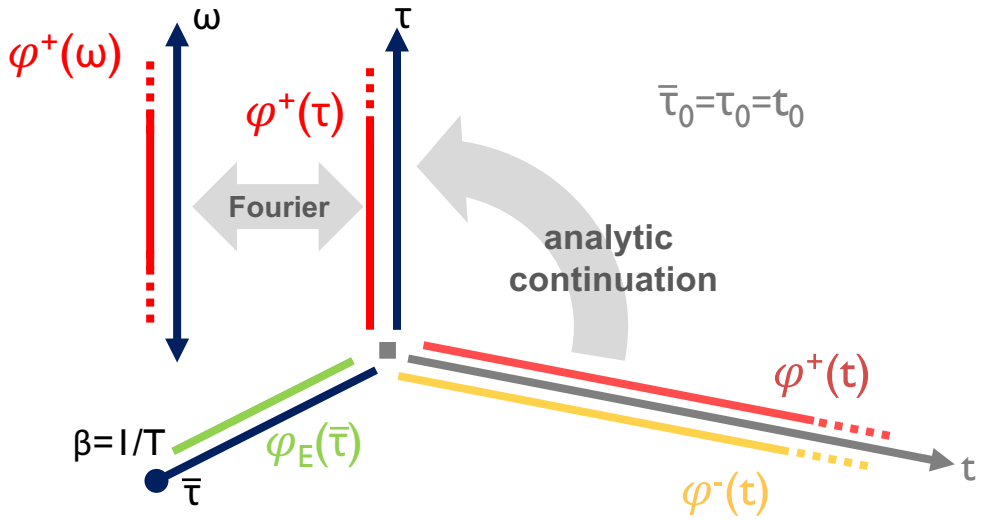

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- Actual numerical setup:
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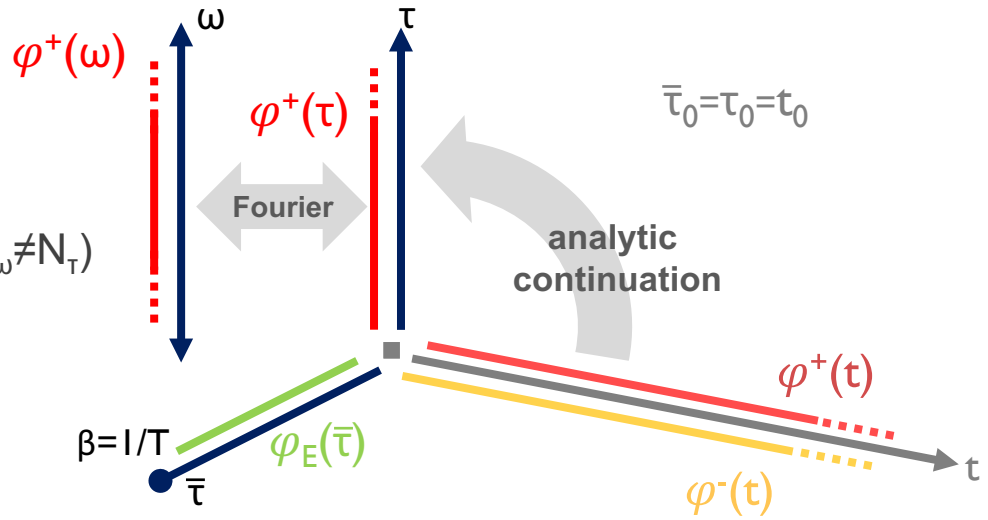
  - Compute $\delta S_E/\delta\varphi+(\omega)$ in Fourier space ($N_\omega \neq N_\tau$)
  - Evaluate $\delta S_E^{int}/\delta\varphi+$ using current $\varphi_E(\tau=0)$
  - Update $\varphi^+(\omega)$



Outline

- Motivation
  - Coherent picture of in-medium heavy-quarkonium from the lattice
- In-medium quarkonium from a lattice EFT (NRQCD)
  - Numerical setup and spectral reconstruction
  - Current T>0 results from realistic full QCD simulations
- Towards improved spectral information from thermal fields
  - Derivation of a novel simulation prescription
  - Current exploratory results from toy models to quenched QCD
- Conclusion

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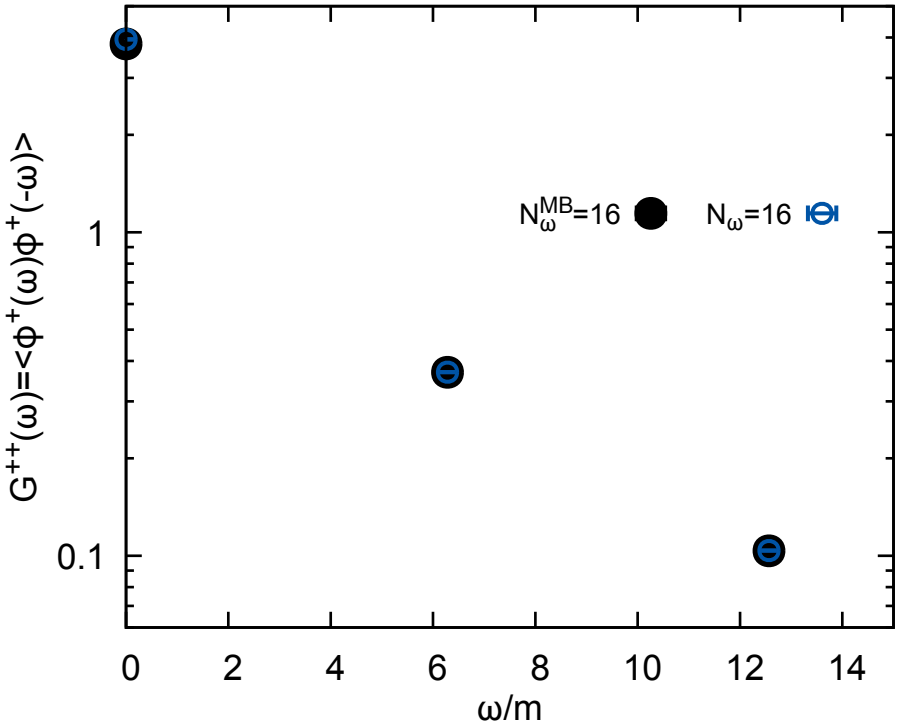

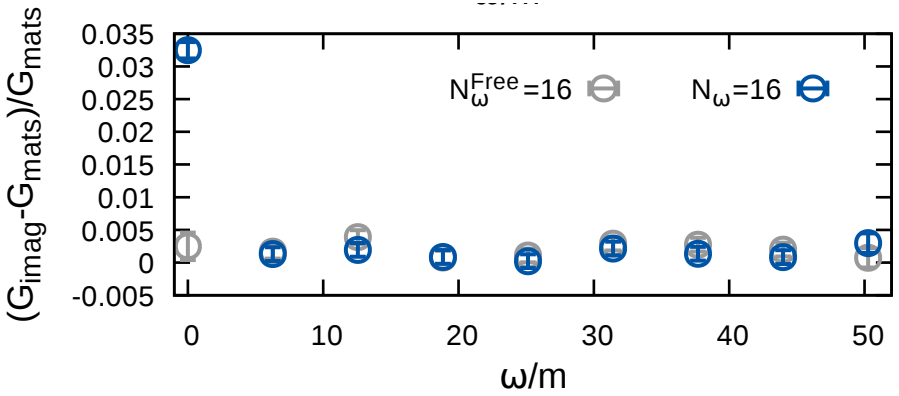

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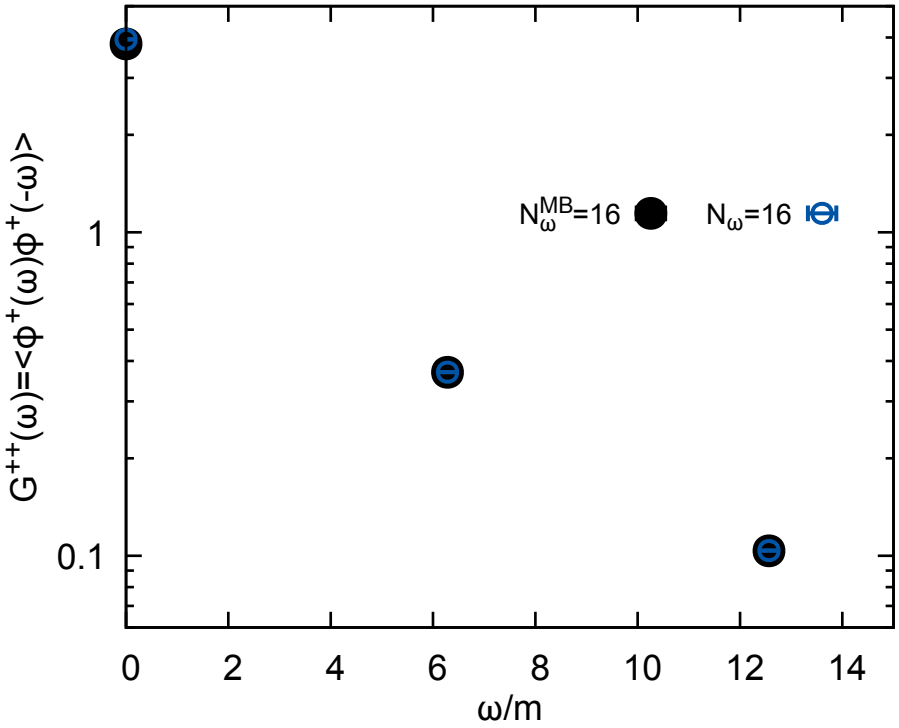

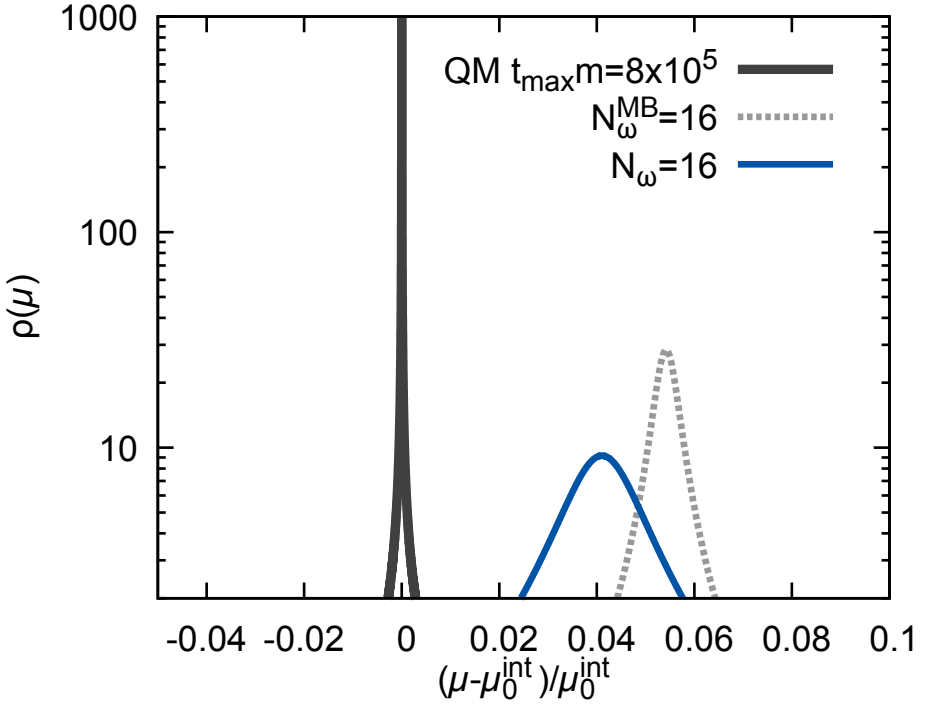

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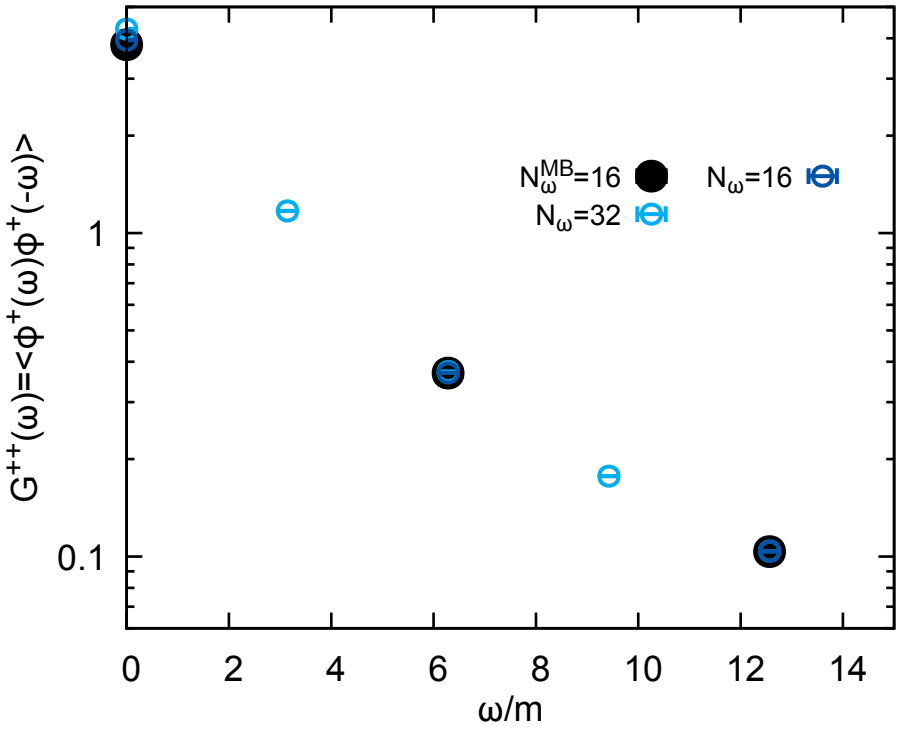

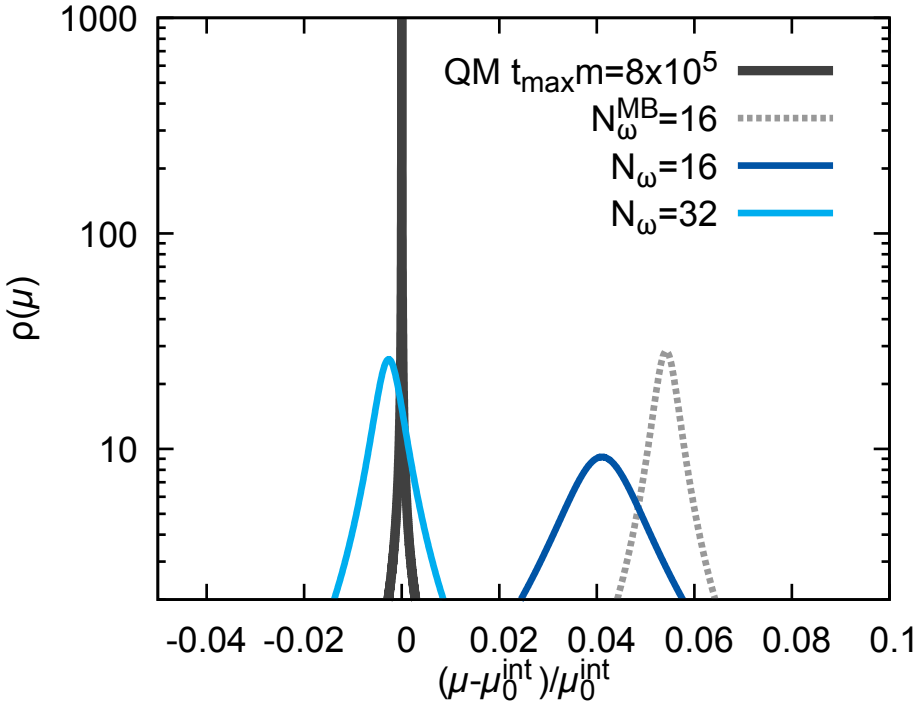

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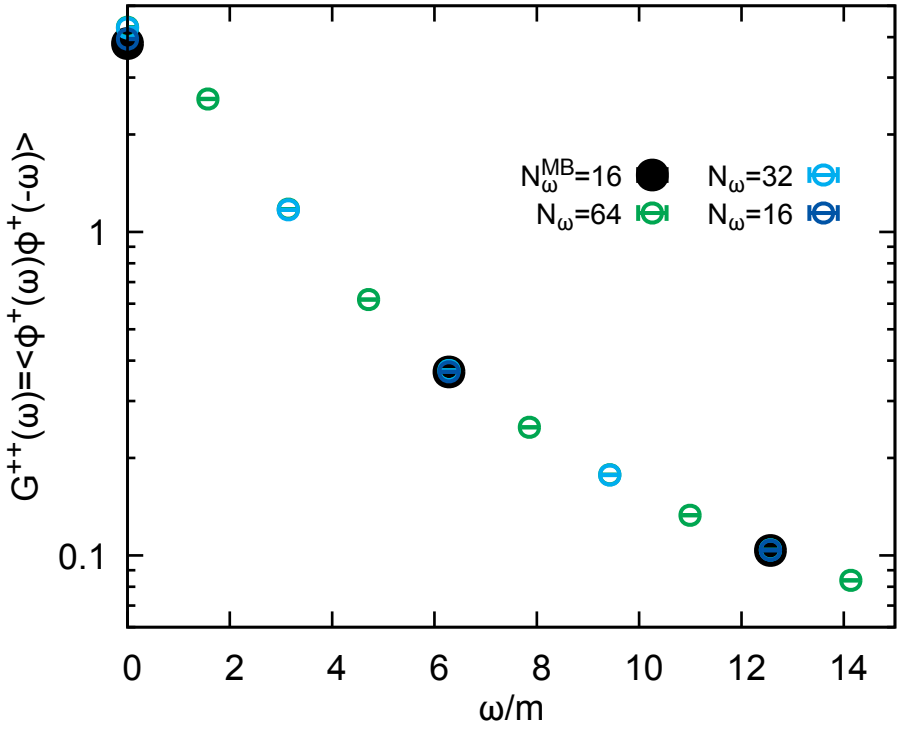

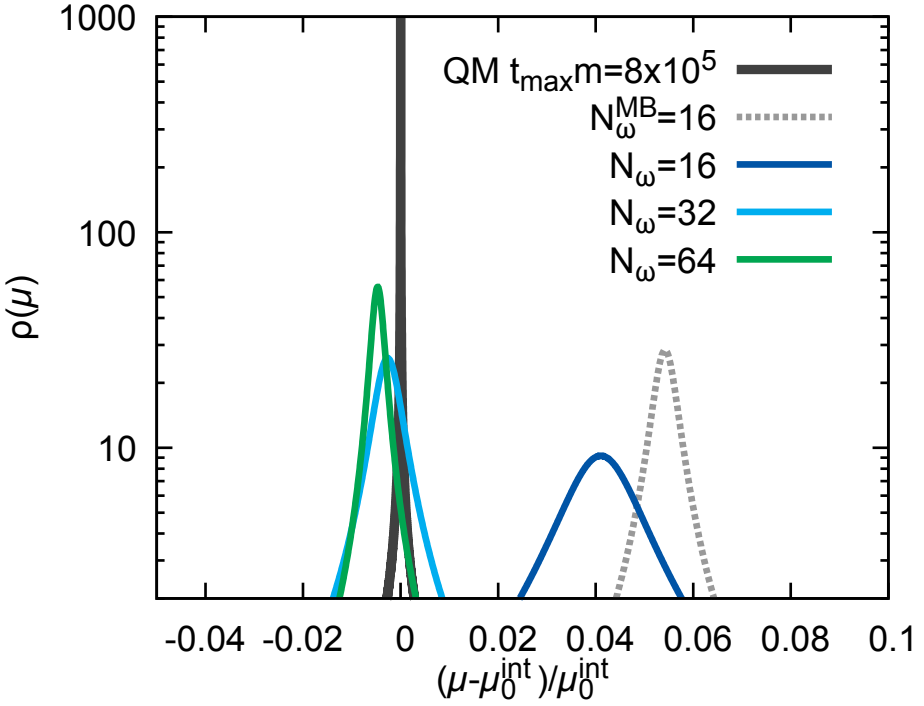

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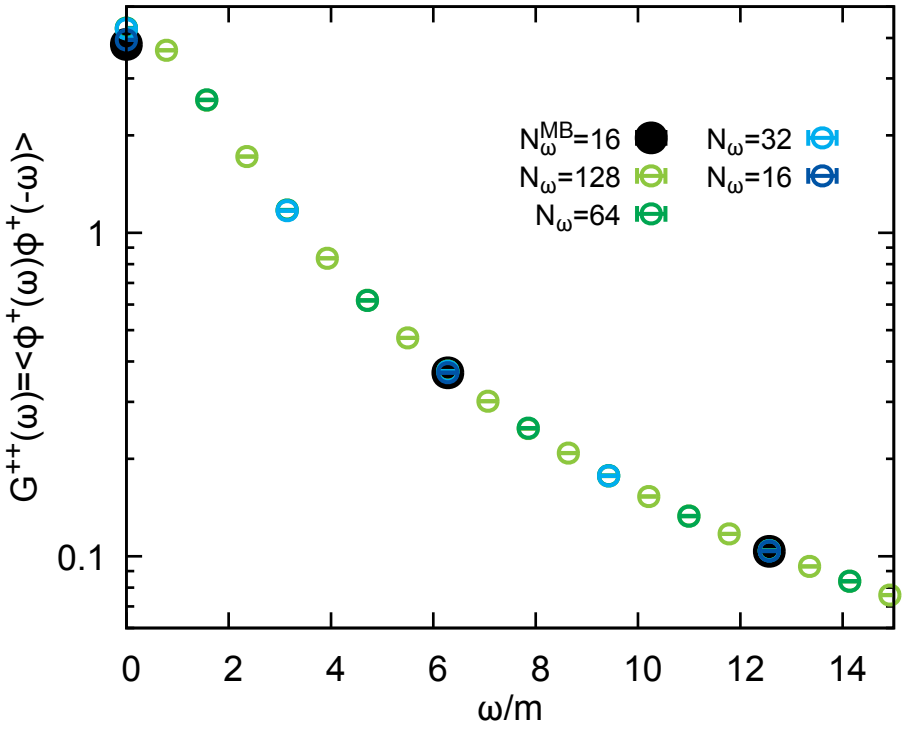

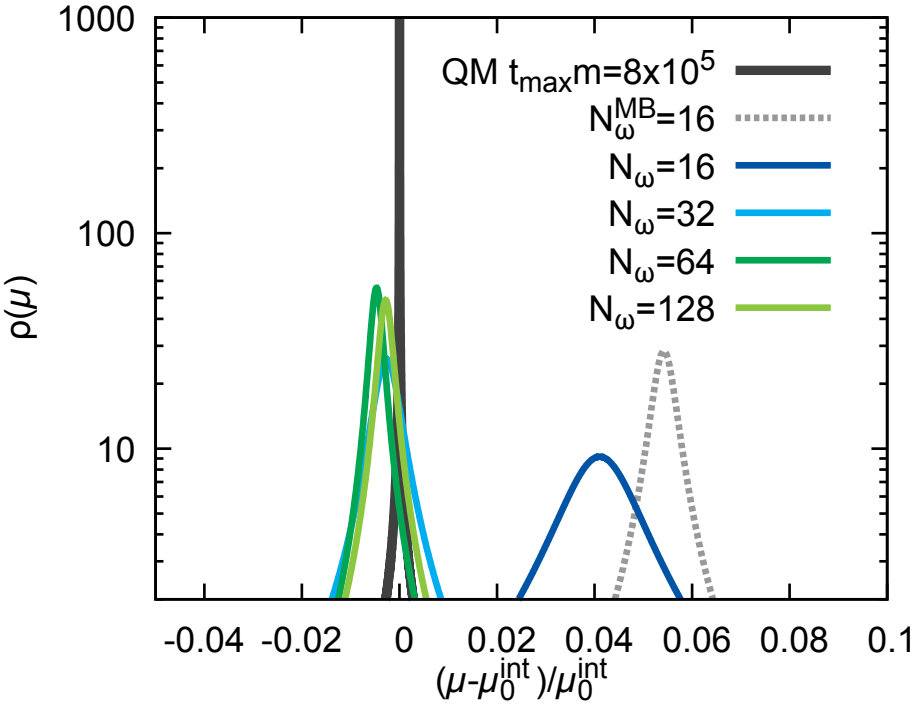

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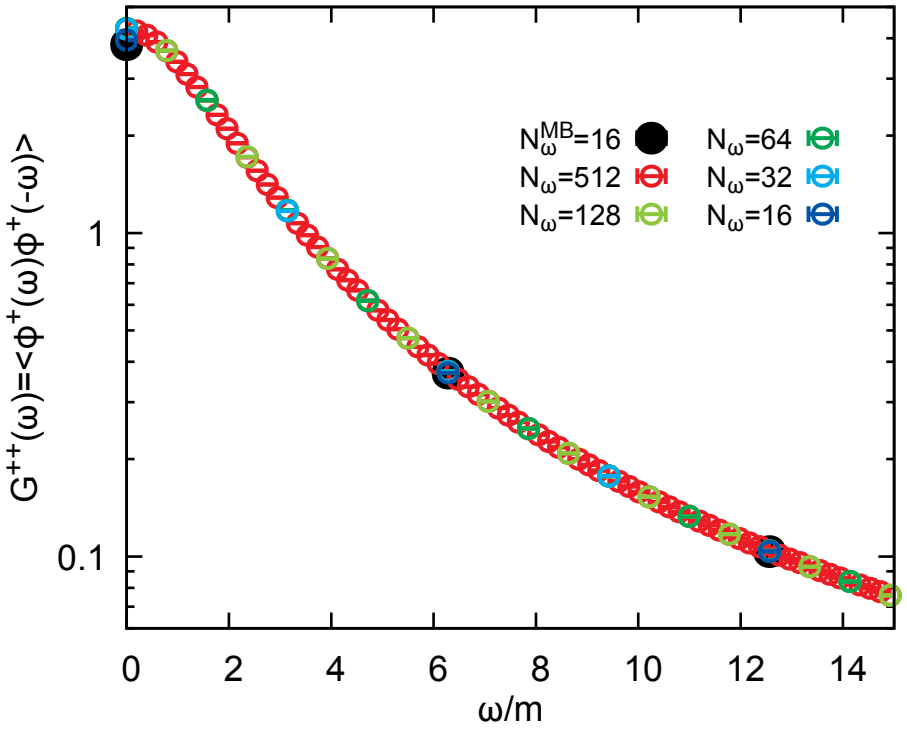

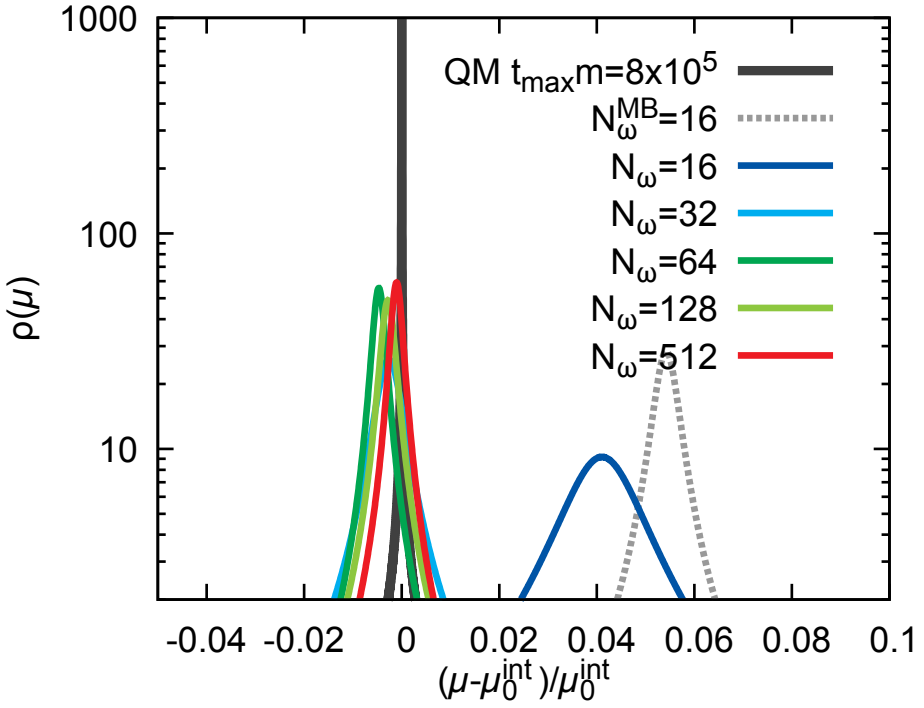

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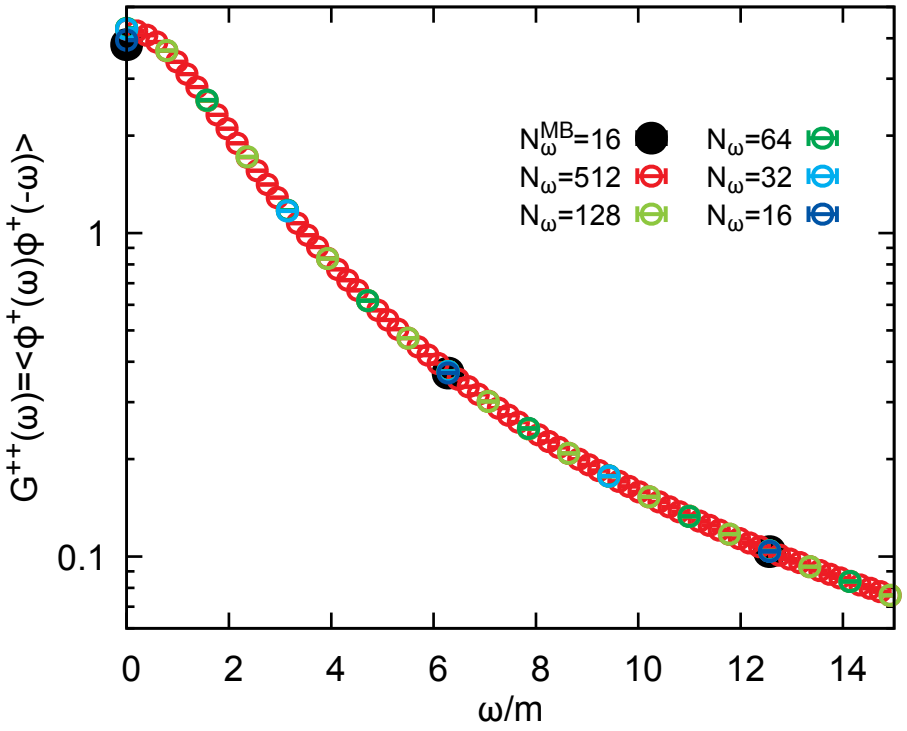

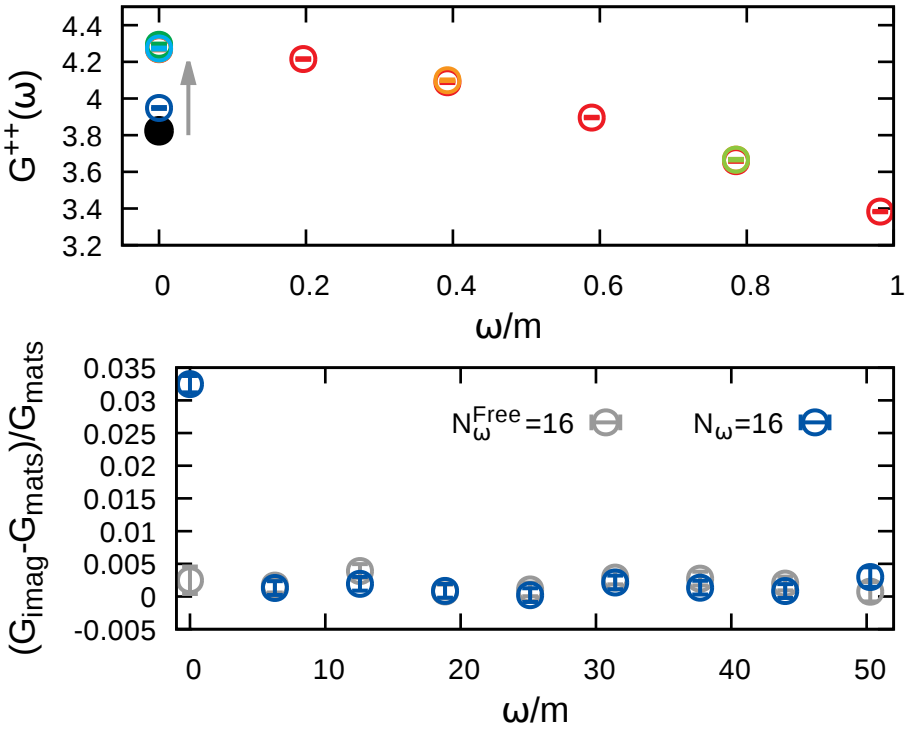

Exploring quenched QCD

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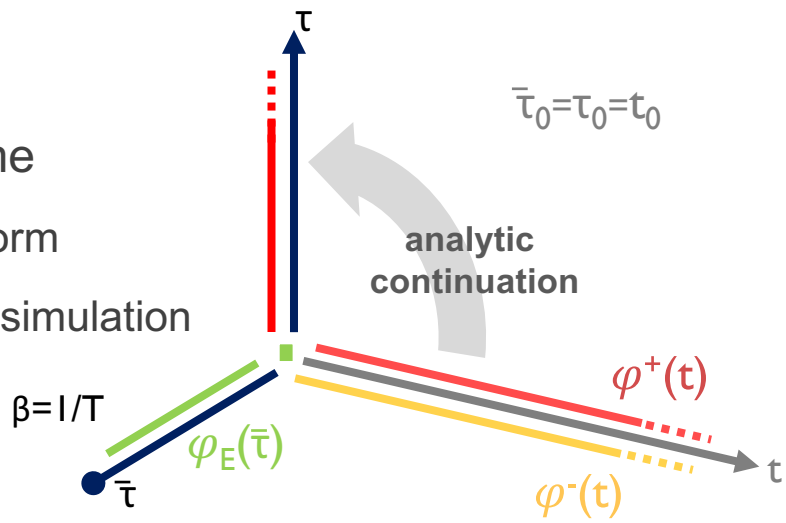

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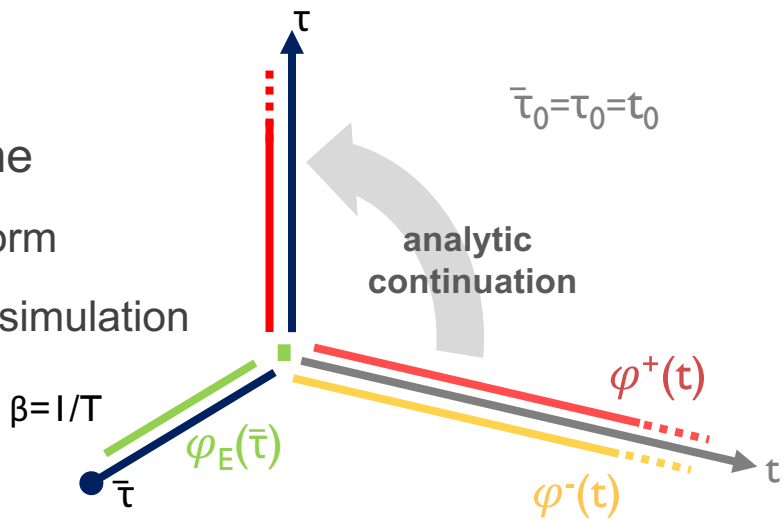

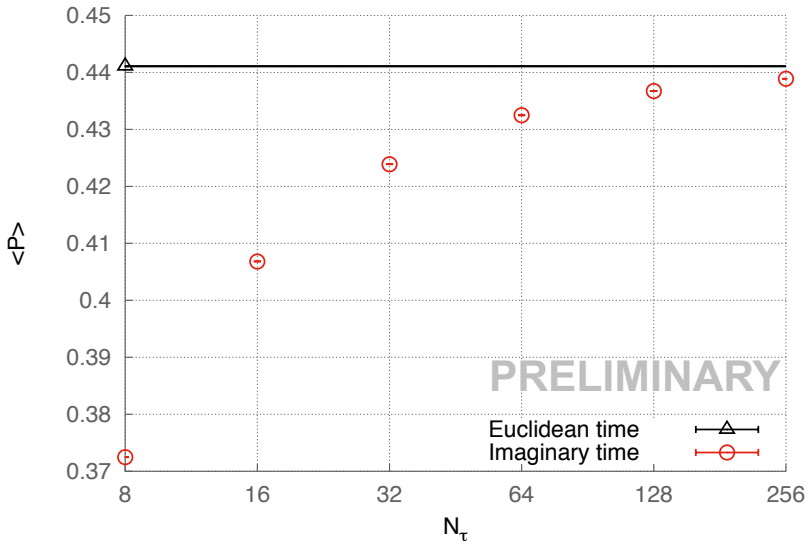

J.M. Pawlowski, A.R., F. Ziegler in preparation

- Naïve approach appears to converge slowly but monotonously to correct results for $N_\tau \to \infty$

Observables in SU(2)

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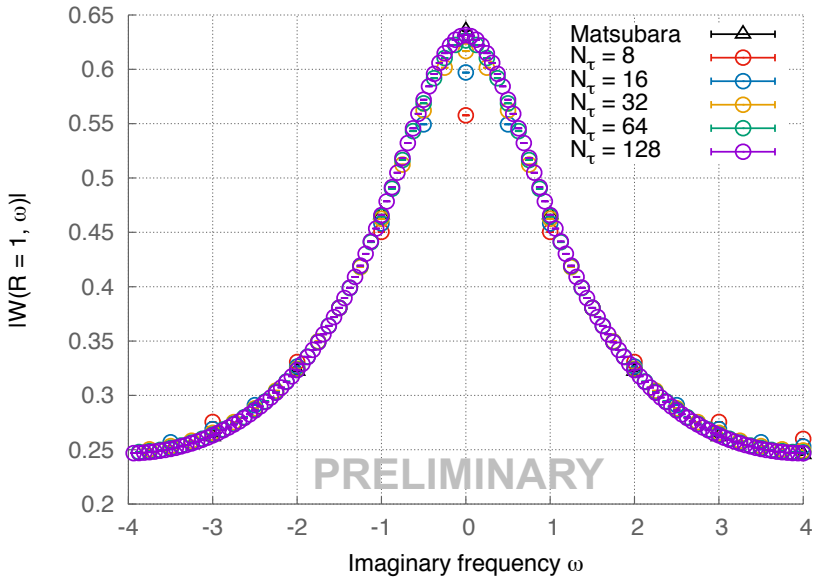

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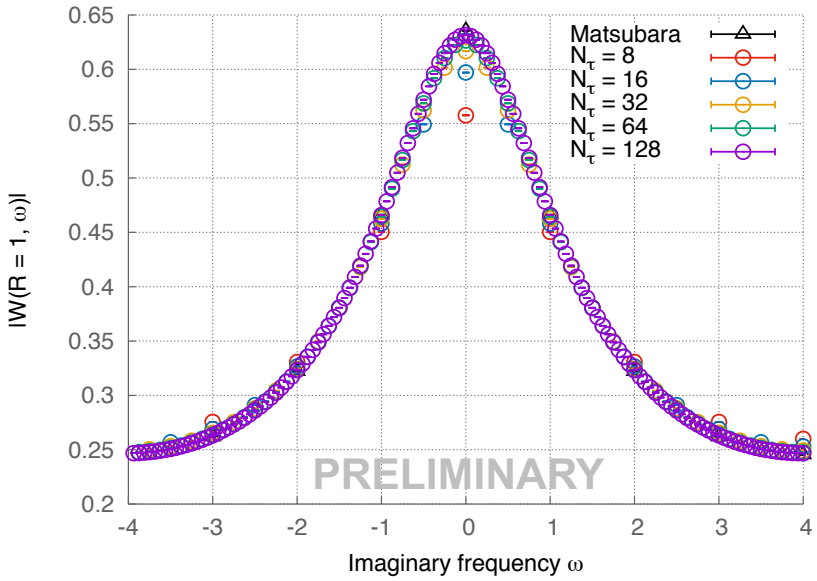

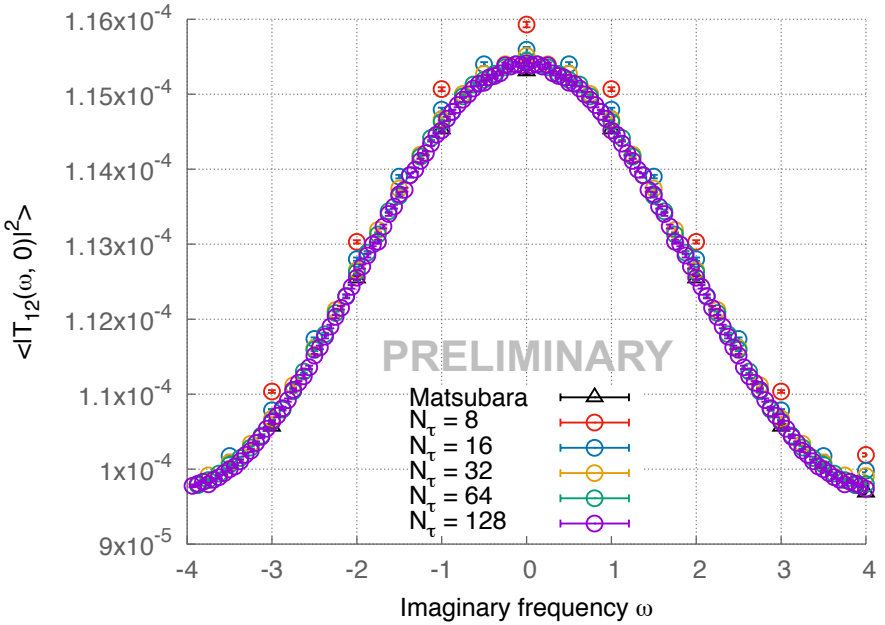

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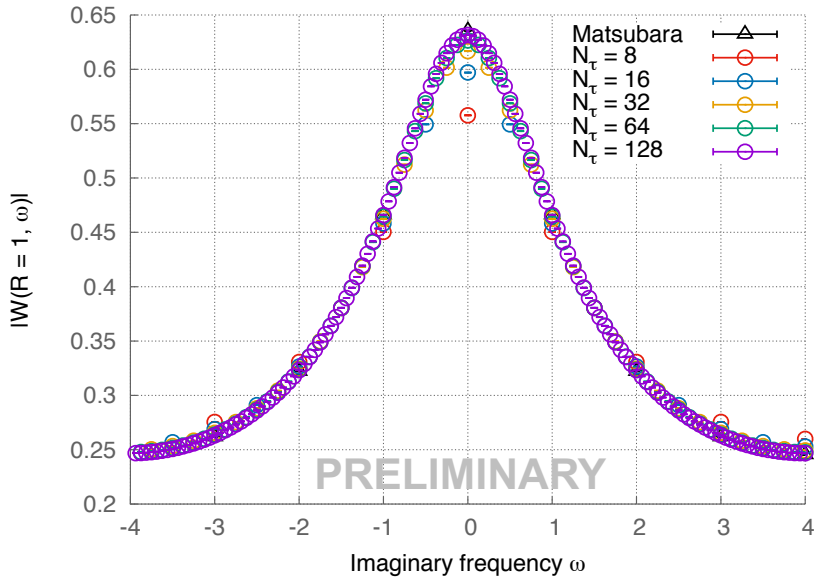

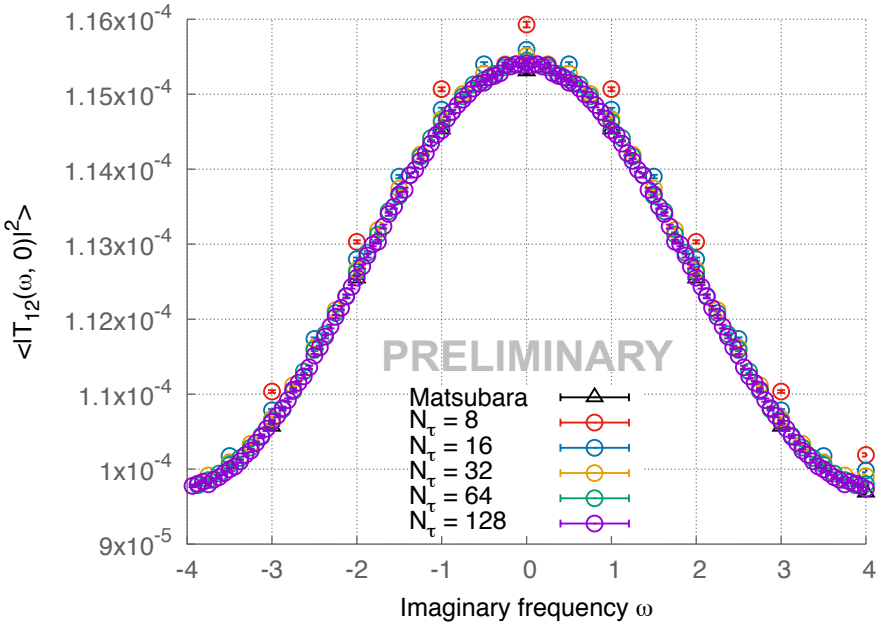

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- Stay tuned for more results in the near future…

Conclusion

- Consistent theory answer to in-medium quarkonium spectra needed
- Updated results from the EFT NRQCD on realistic Nf=2+1 lattices
  S.Kim, P. Petreczky, A.R.: Phys.Rev. D91 (2015) 54511, Nucl.Phys. A956 (2016) 713 and work in progress
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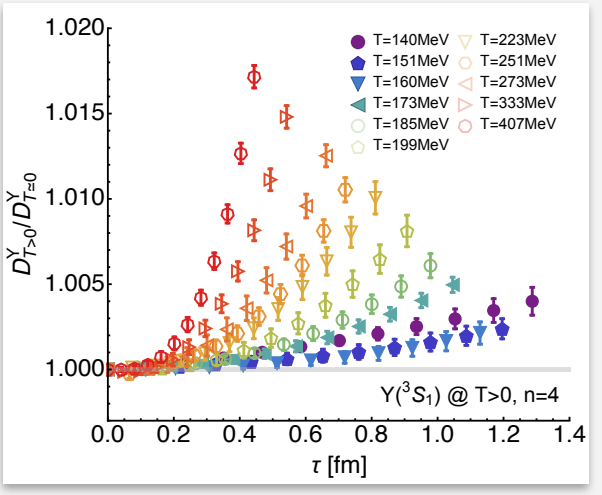
  - Promising results in a **toy model (0+1d)** and ongoing work on **(3+1)d SU(2) Yang-Mills**
    J. Pawlowski, A.R., F. Ziegler in progress

Thank you for your attention

T>0 effects in QQ̄ correlators

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



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

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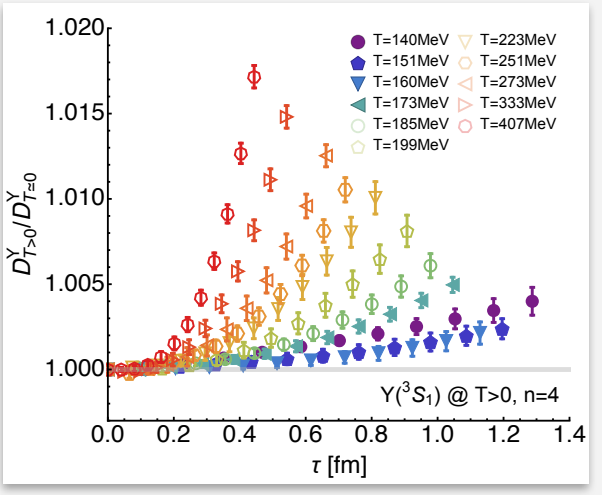

S.Kim, P.Petreczky, A.R. in preparation

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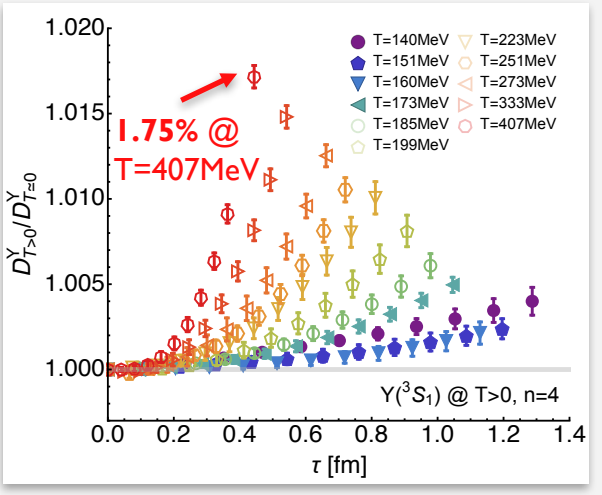

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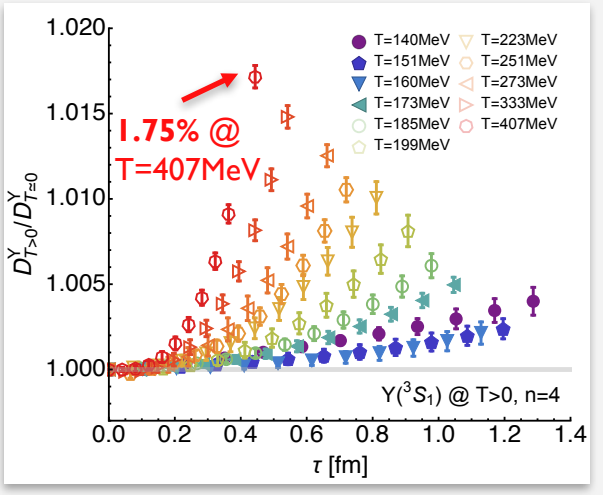
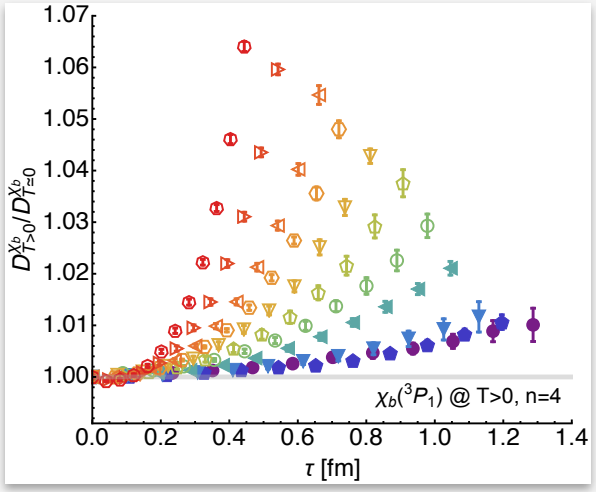


S.Kim, P.Petreczky, A.R. in preparation

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



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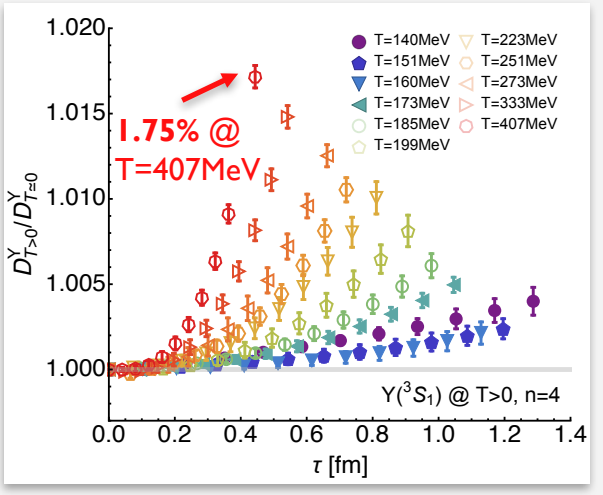

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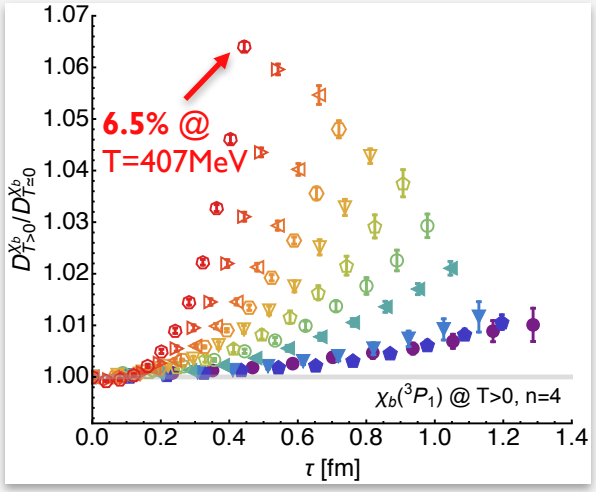

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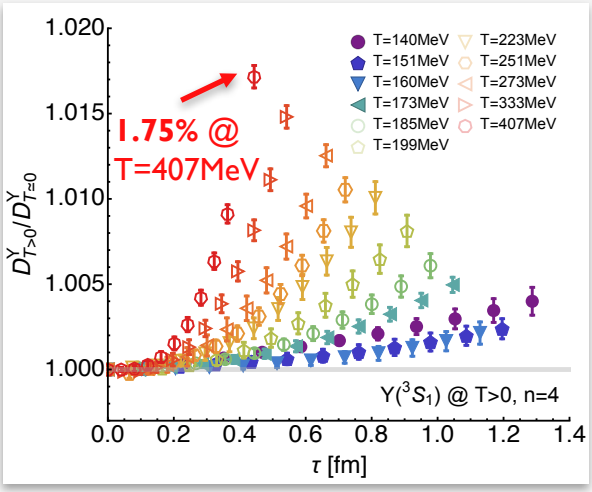

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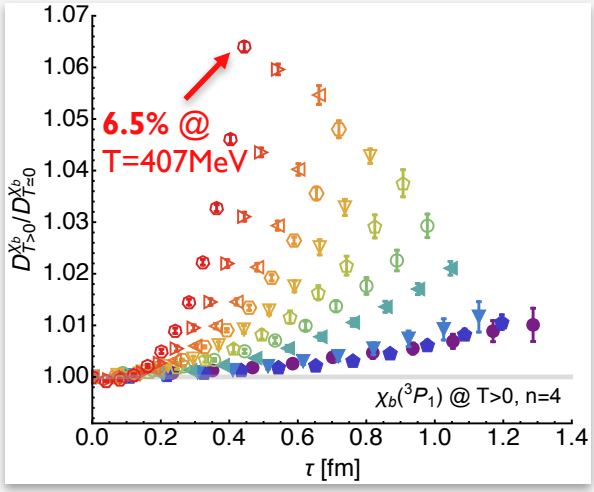

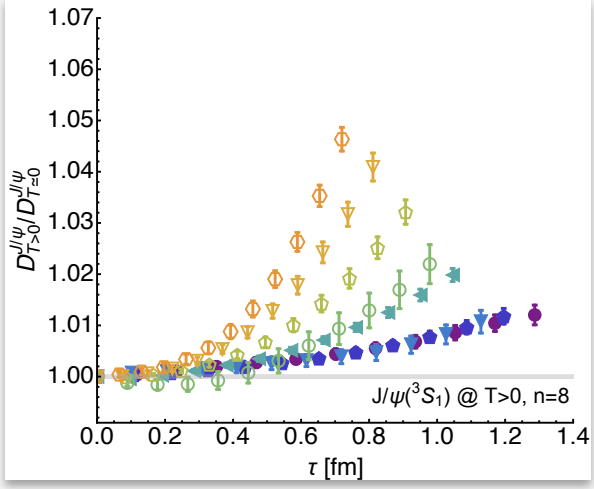

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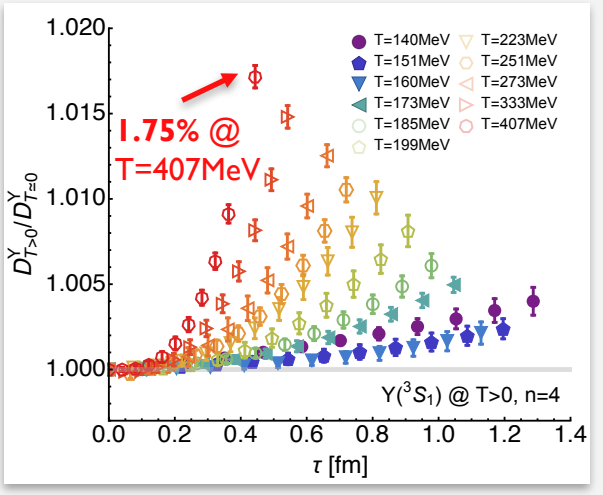

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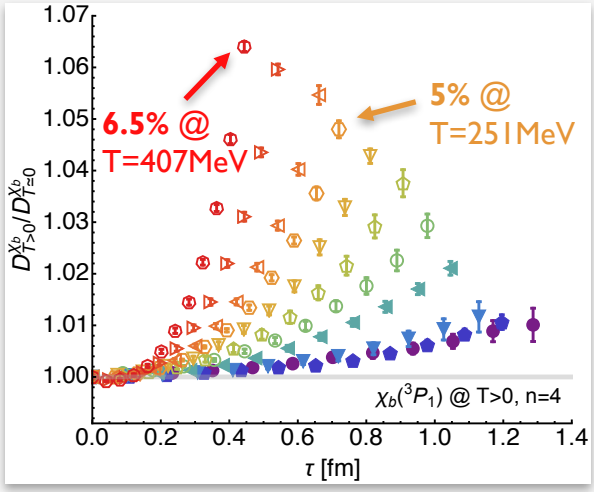

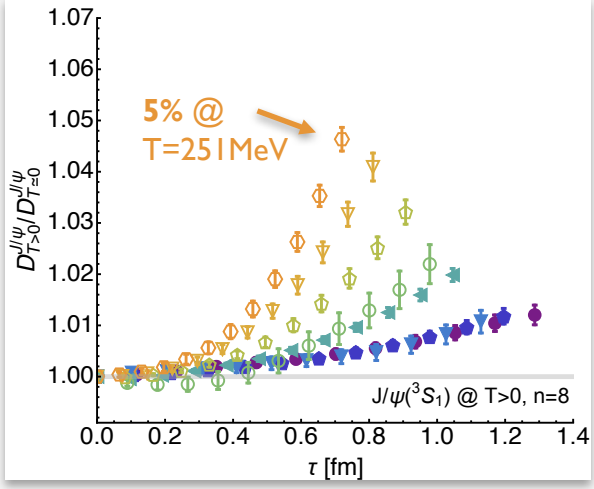

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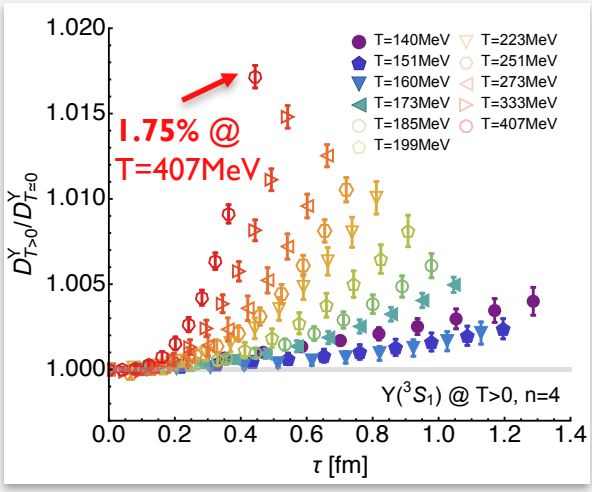

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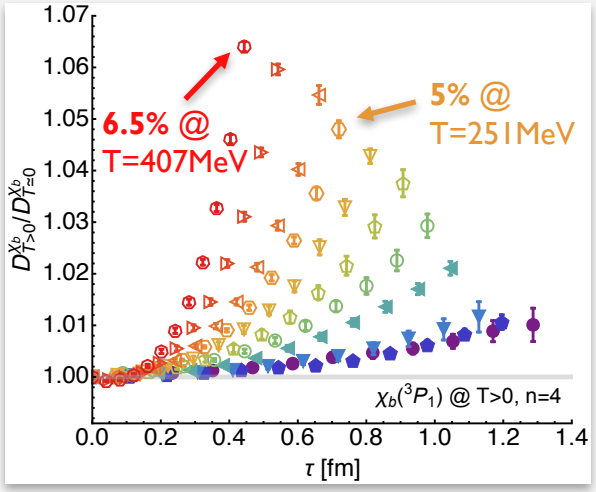
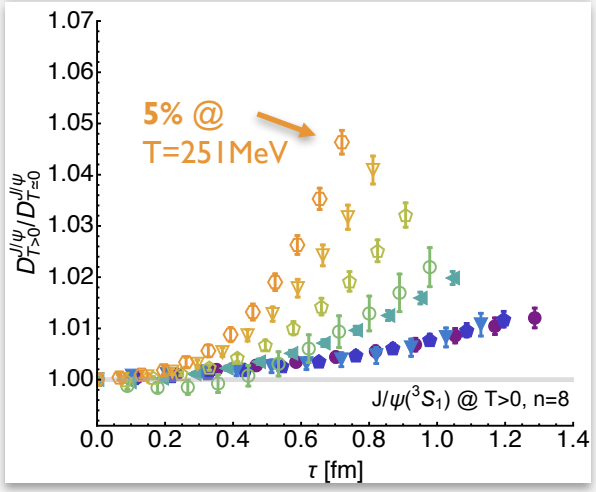
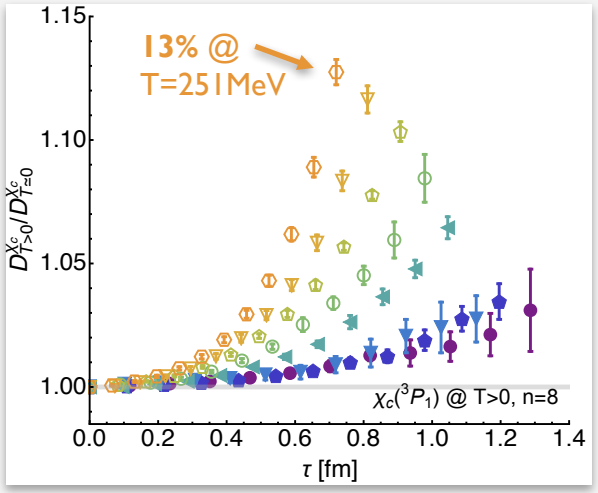


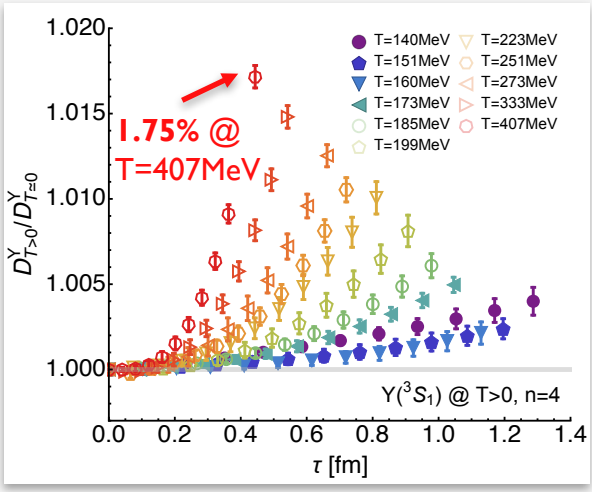


E_{bind} (T=0)~200MeV



T>0 effects in QQ̄ correlators

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



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- Upsilon shows non-monotonous behavior around T~T_C
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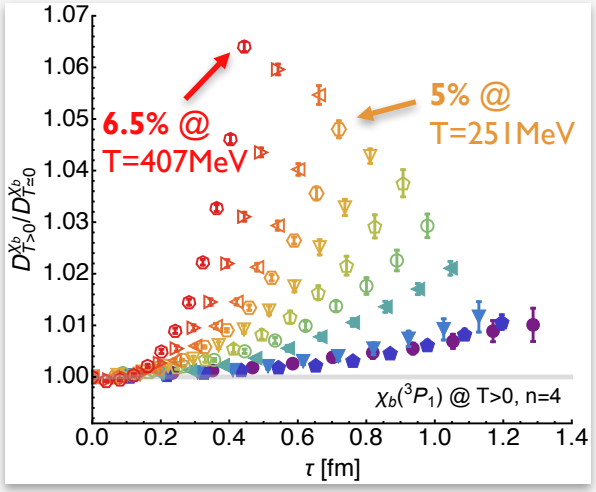
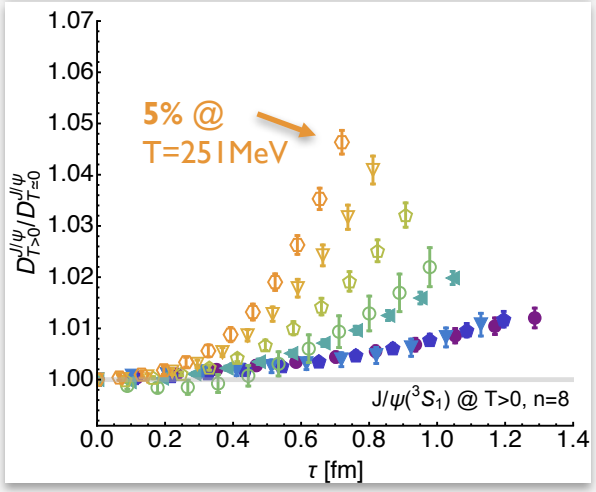
- Hierarchical T>0 modification w.r.t. vacuum binding energy

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





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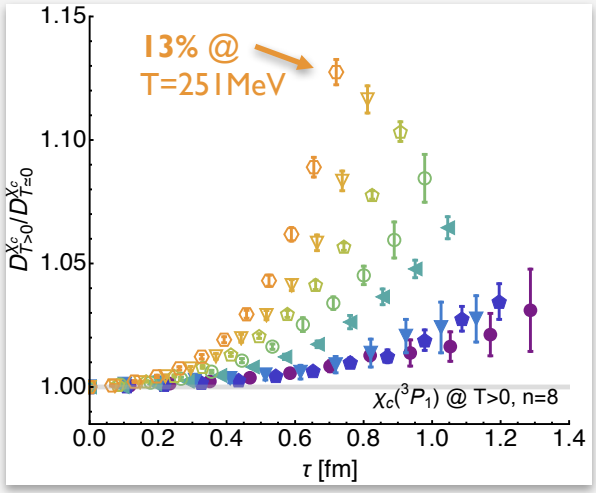
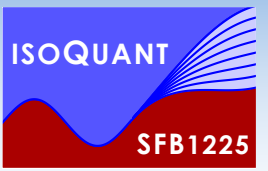


NRQCD P-wave spectra at T>0



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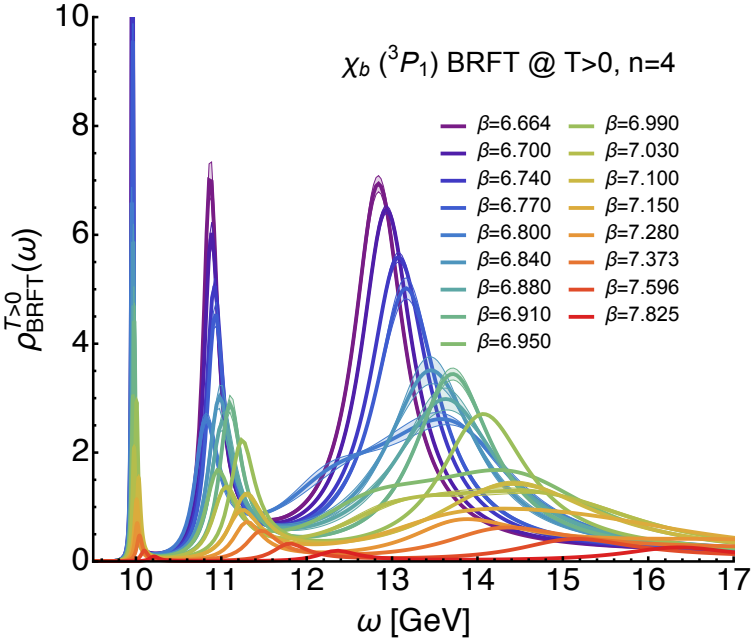
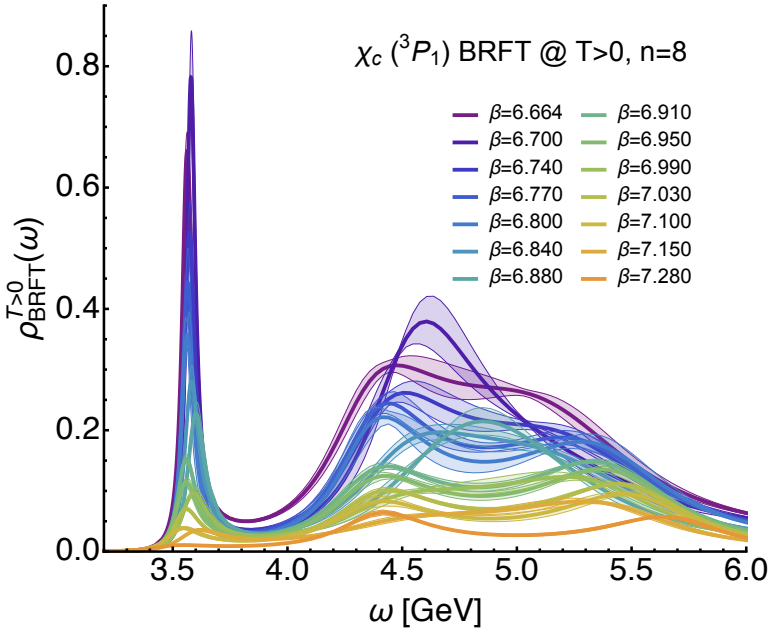
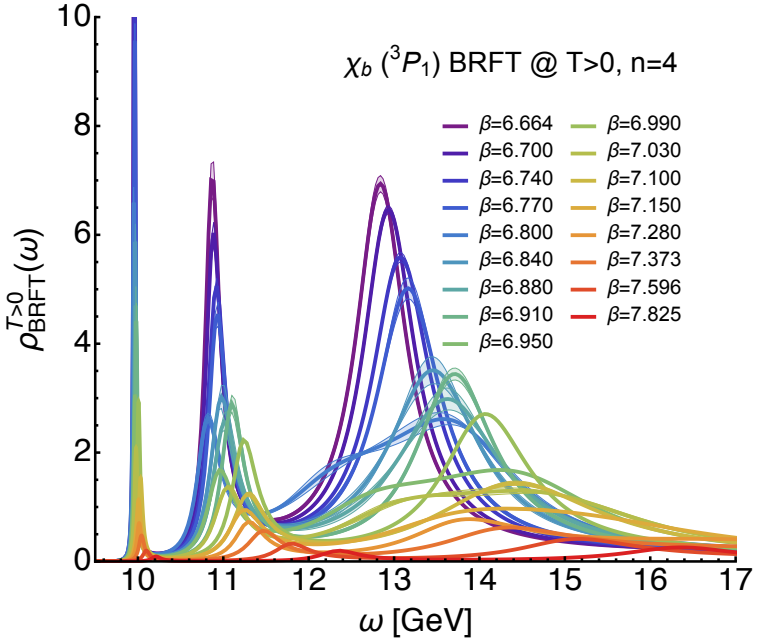
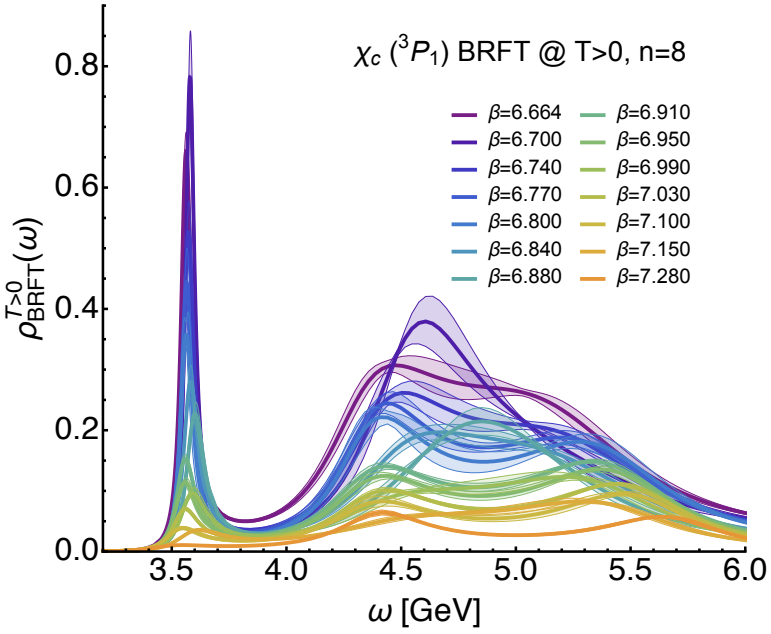




- Lower signal to noise ratio in underlying correlators makes reconstruction less precise

NRQCD P-wave spectra at T>0





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

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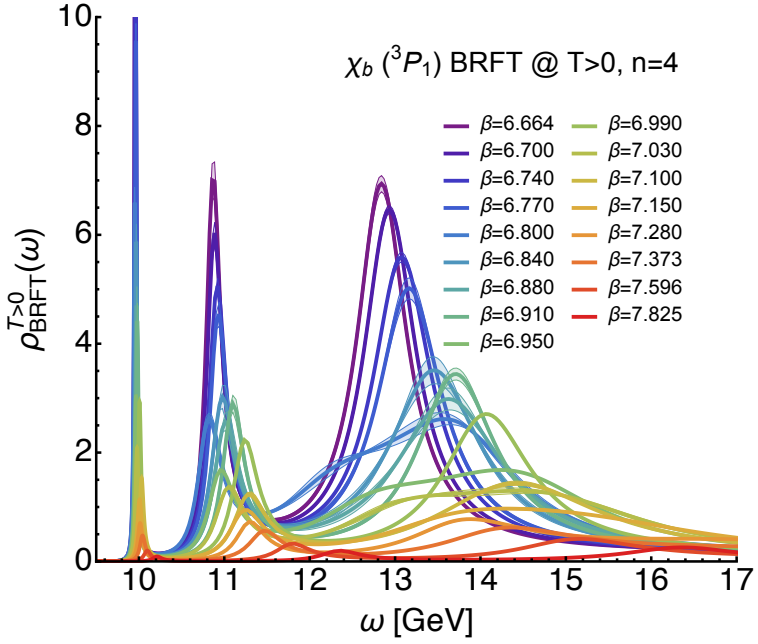

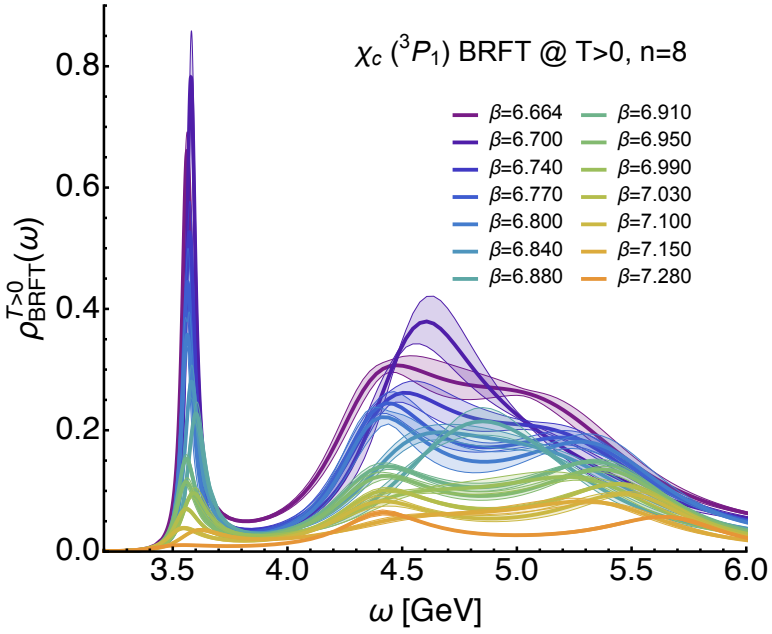

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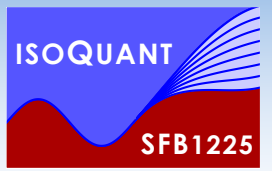
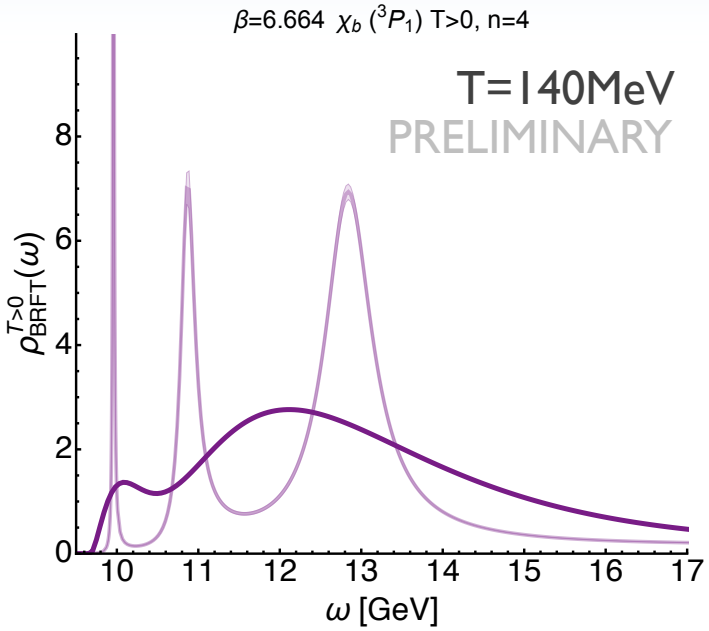
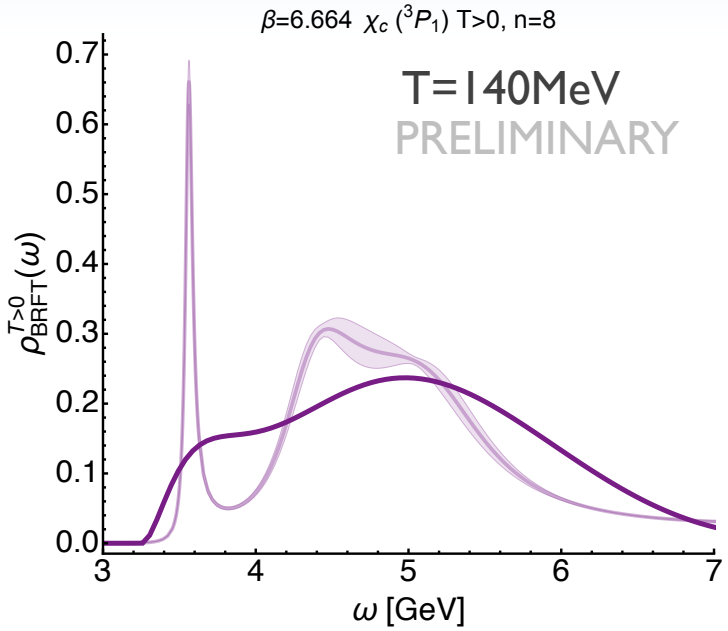
- Lower signal to noise ratio in underlying correlators makes reconstruction less precise
- Ground state well resolved and well separated from higher lying structures
- Gradual broadening and shifting of lowest lying peak visible

Survival of ground state signals?



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





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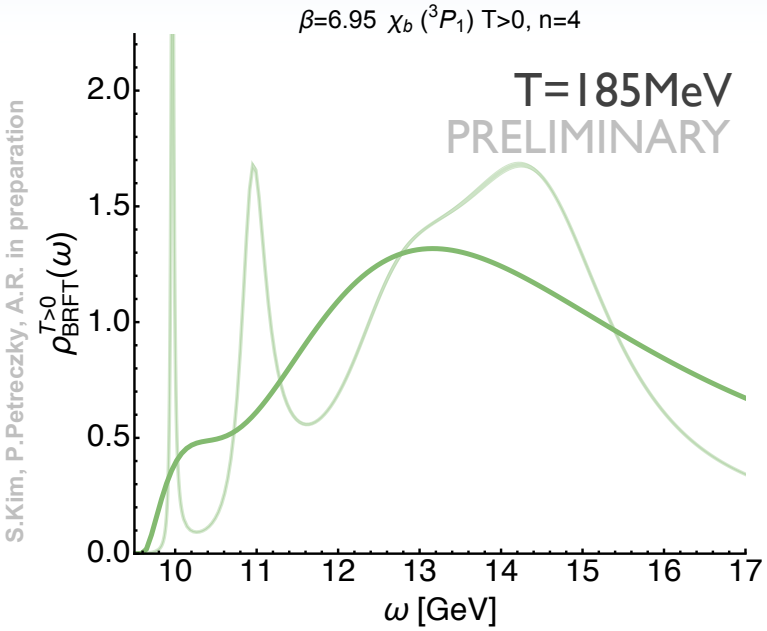

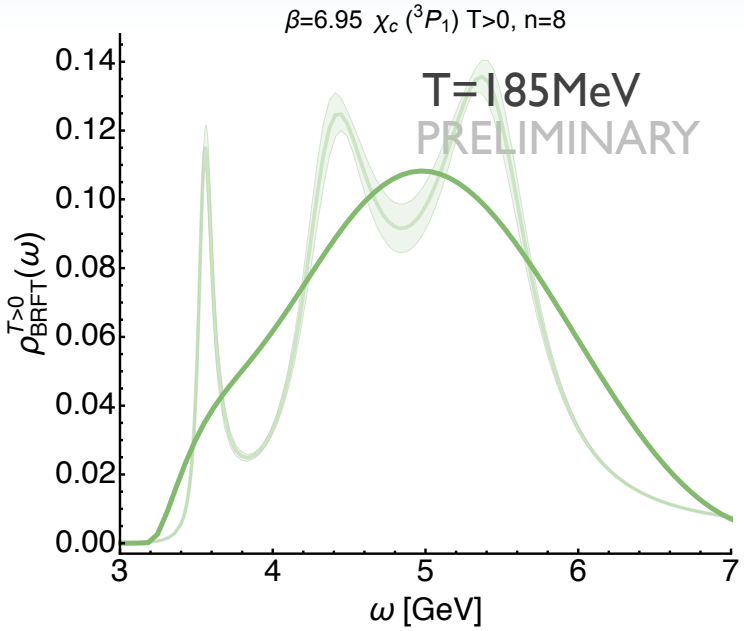

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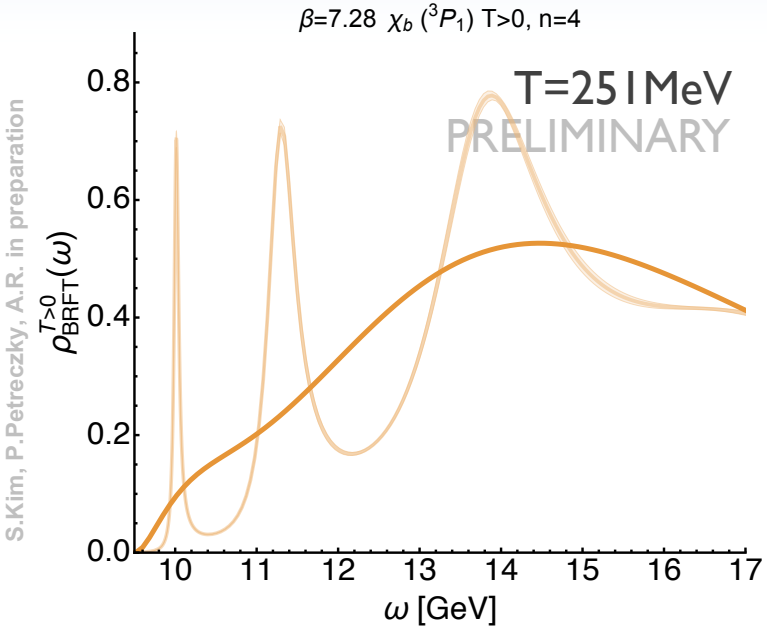
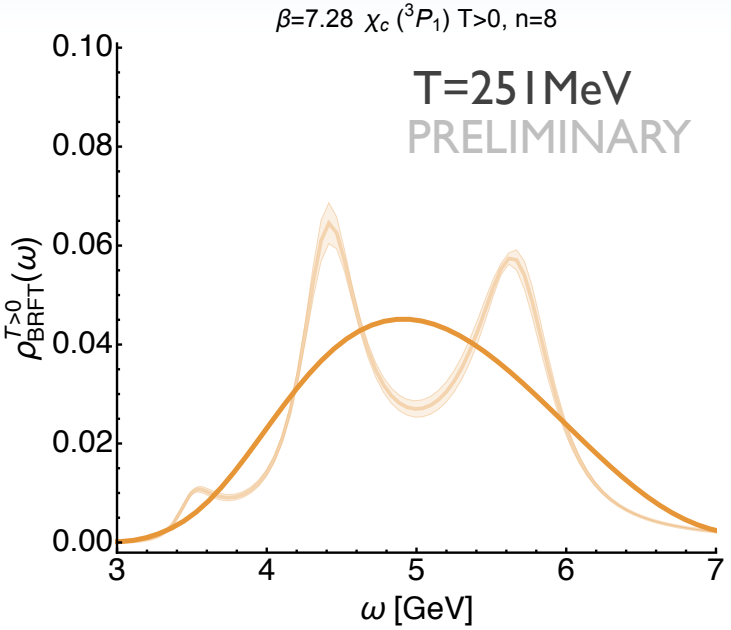


S.Kim, P.Petreczky, A.R. in preparation



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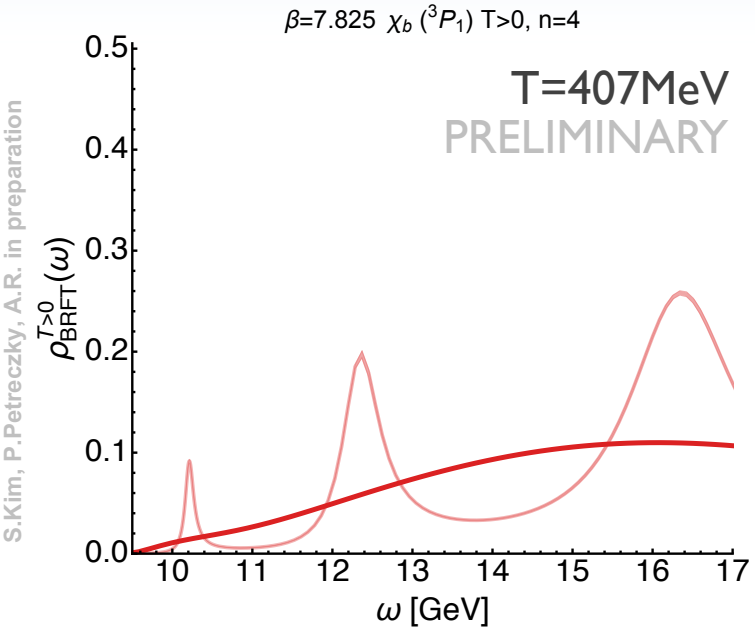

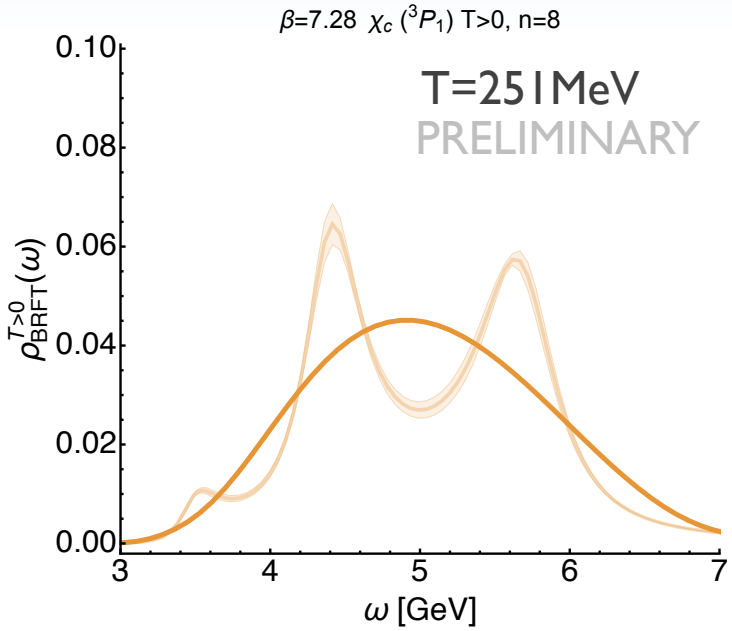

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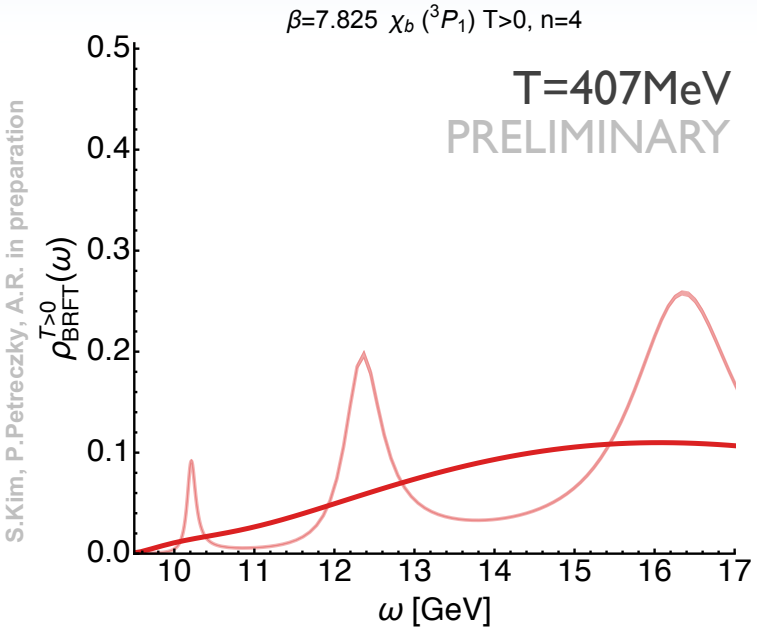
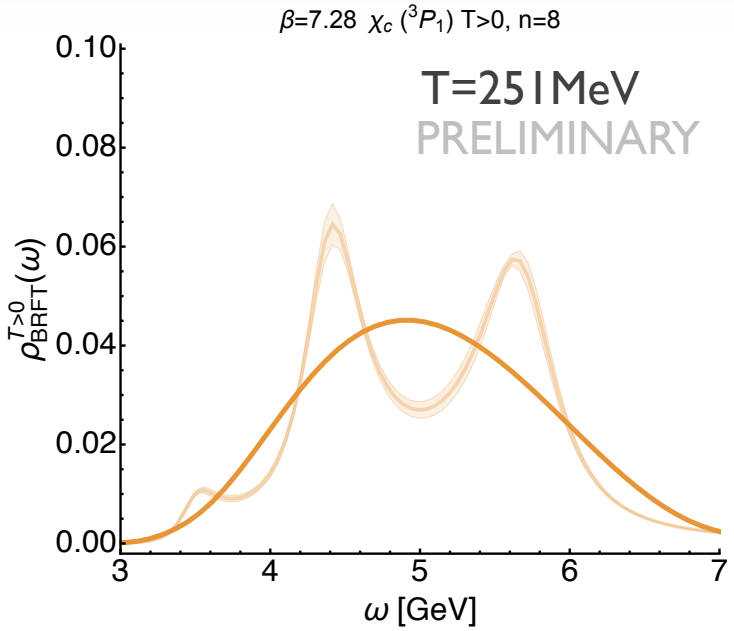
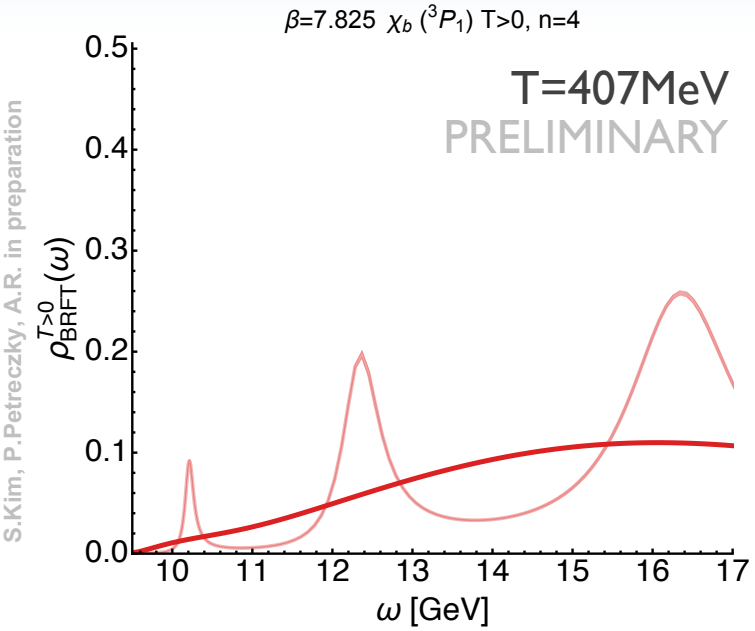
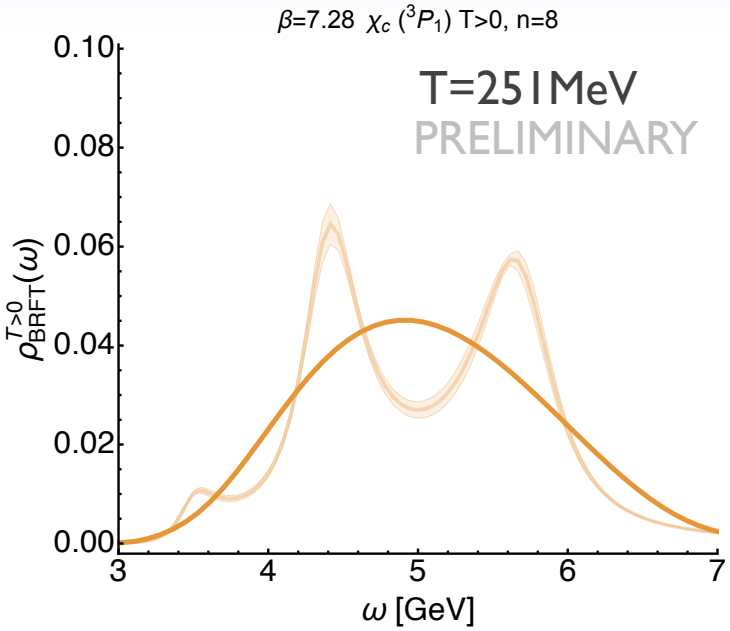




- New “low-gain” BR method shows gradual weakening of ground state signal

Survival of ground state signals?

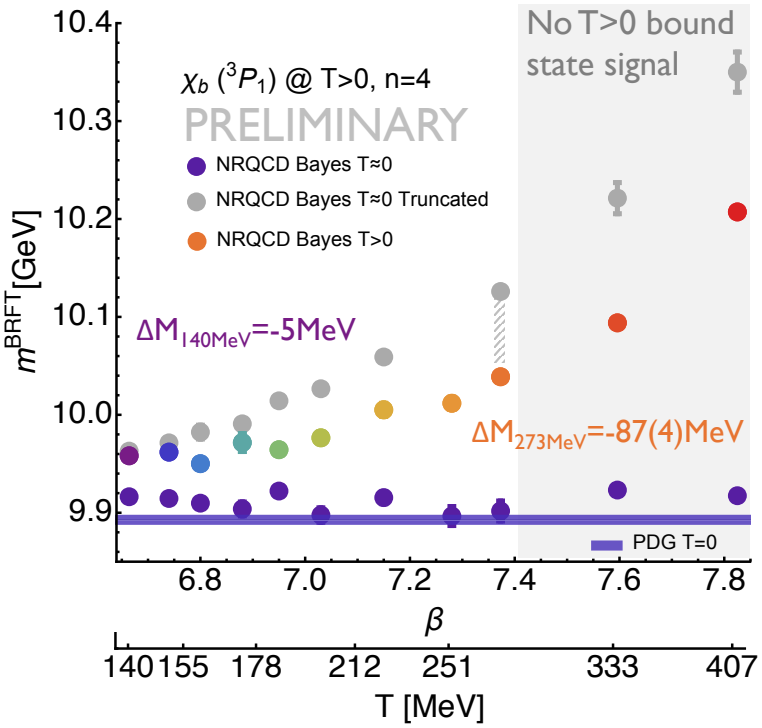


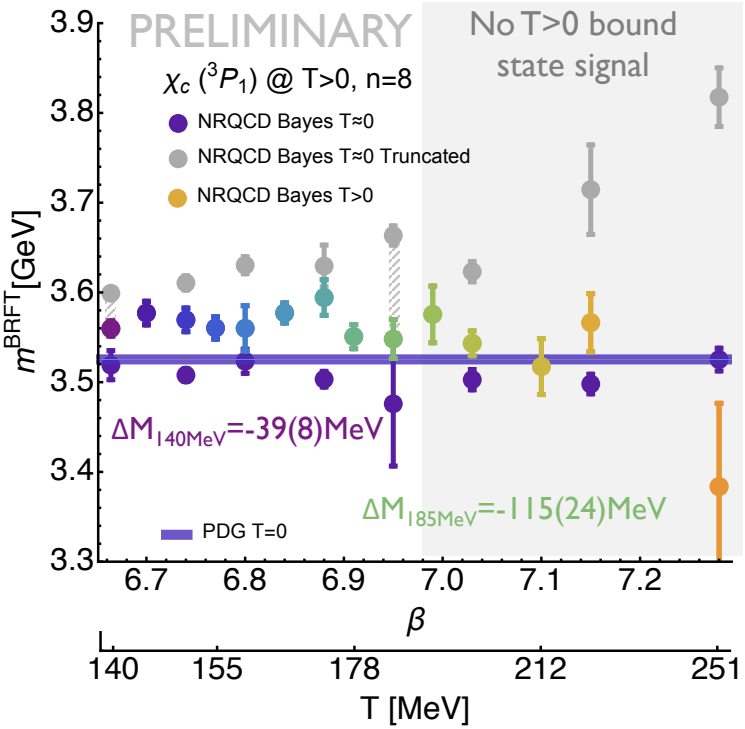


- New “low-gain” BR method shows gradual weakening of ground state signal
- Genuine bound state signal lost at intermediate temperatures

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

In-medium P-wave mass shifts



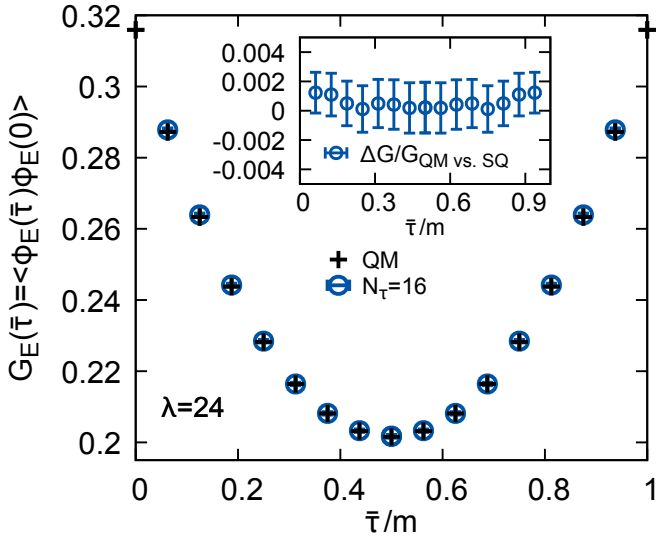


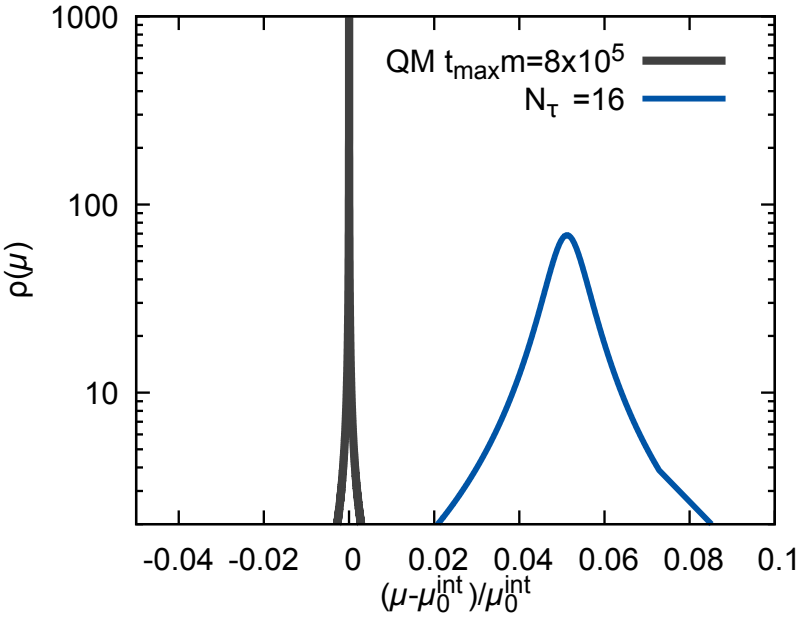
S.Kim, P.Petreczky, A.R. in preparation

- 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

(0+1d) scalar field toy model (I)

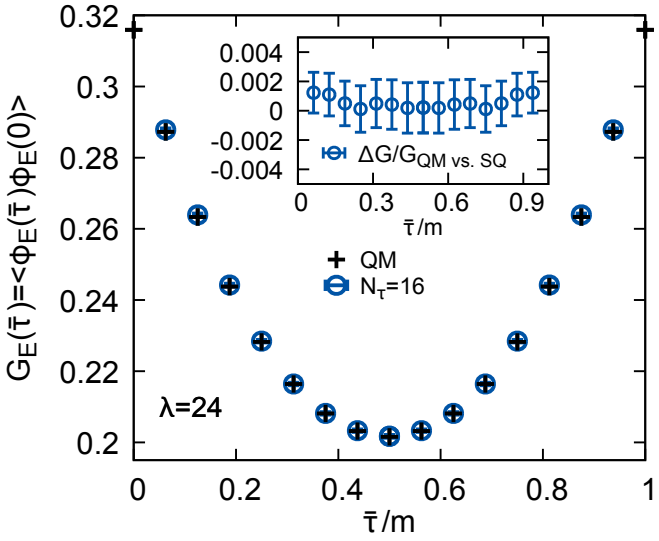
- Standard update for φ_E with N_τ=16 m=1 λ=24 $N_\tau d\tau$=1 (compare to QM of A.H.O.)

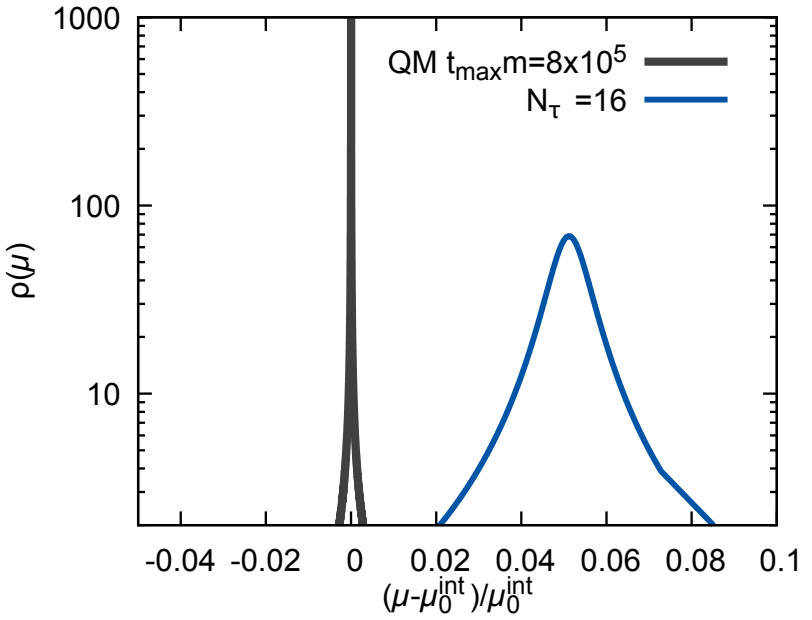




(0+1d) scalar field toy model (I)

- Standard update for φ_E with N_τ=16 m=1 λ=24 $N_\tau d\tau$=1 (compare to QM of A.H.O.)
- Let us check, whether we can improve spectral reconstruction by increasing N_τ
- Decreasing $d\tau$ increases drift in $\partial_{t_5}\varphi_E(\bar{\tau}) = -\frac{\delta S_E[\varphi_E]}{\delta\varphi_E(\bar{\tau})} + \eta(\bar{\tau})$: need to reduce dt_5





(0+1d) scalar field toy model (I)

- Standard update for φ_E with N_τ=16 m=1 λ=24 $N_\tau d\tau$=1 (compare to QM of A.H.O.)
- Let us check, whether we can improve spectral reconstruction by increasing N_τ
- Decreasing dτ increases drift in $\partial_{t_5}\varphi_E(\bar{\tau}) = -\frac{\delta S_E[\varphi_E]}{\delta\varphi_E(\bar{\tau})} + \eta(\bar{\tau})$: need to reduce dt_5