In-medium Heavy Quarkonium properties from effective field theory on the lattice

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. D91 (2015) 054511
S.Kim, P. Petreczky, A.R. in preparation

2015 RHIC & AGS Annual Users' Meeting – BNL Upton, NY USA – June 9th

Motivation: Heavy-Ion Collisions

- Starting with RHIC: golden age of relativistic heavy-ion collision experiments

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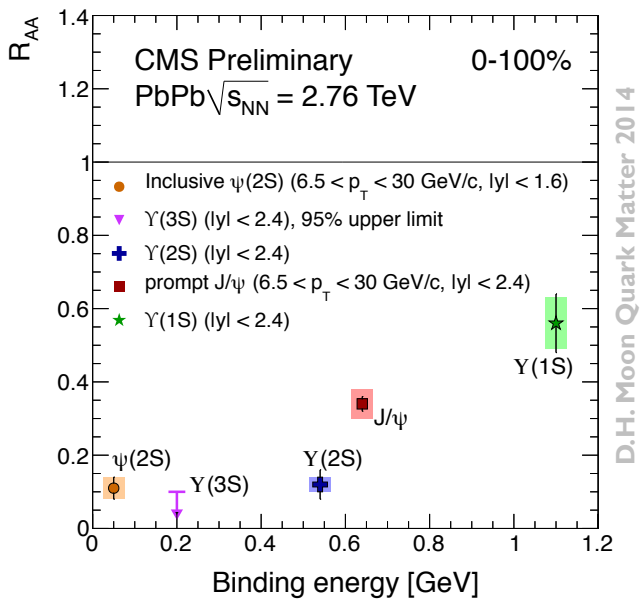
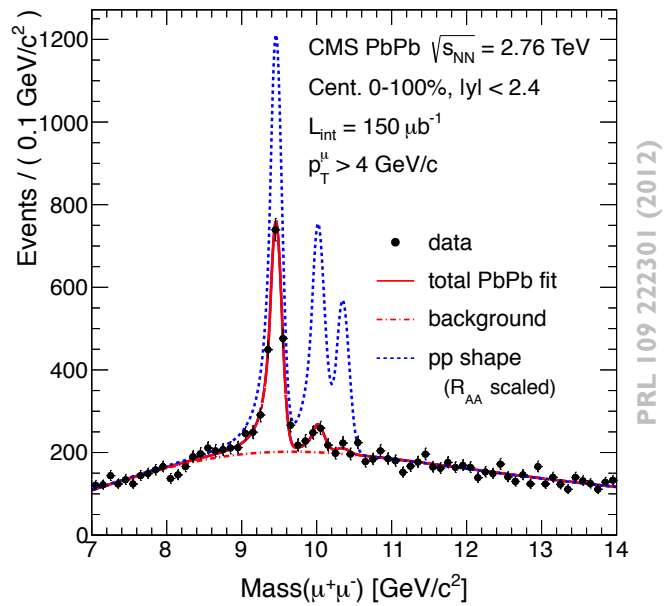
- Our interest: probes susceptible to medium but distinguishable $Q_{probe} >> T_{med}$

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





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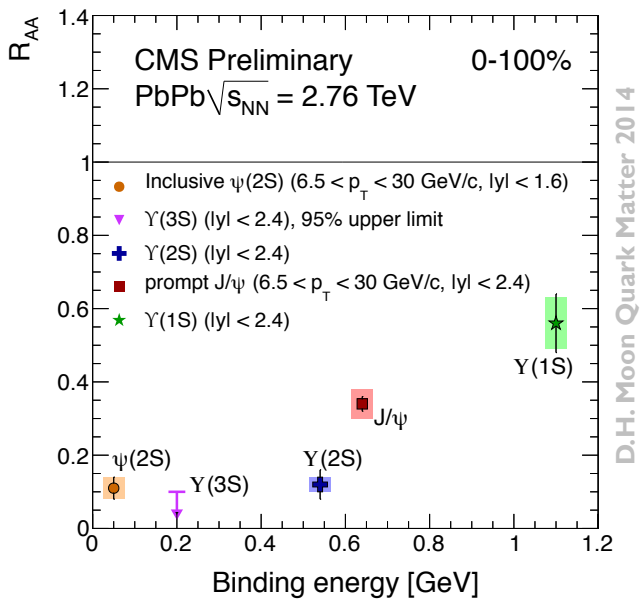

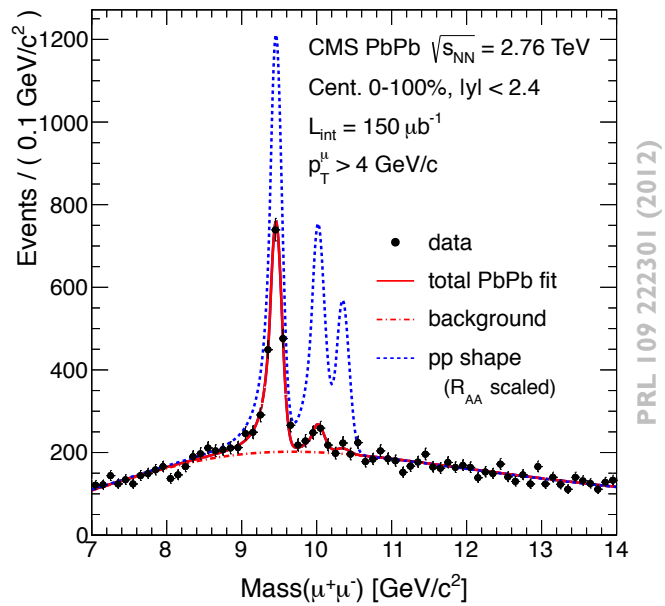

- Goal: 1st principles understanding of $q\bar{q}$ modification in the perfect liquid

Quarkonium from first principles

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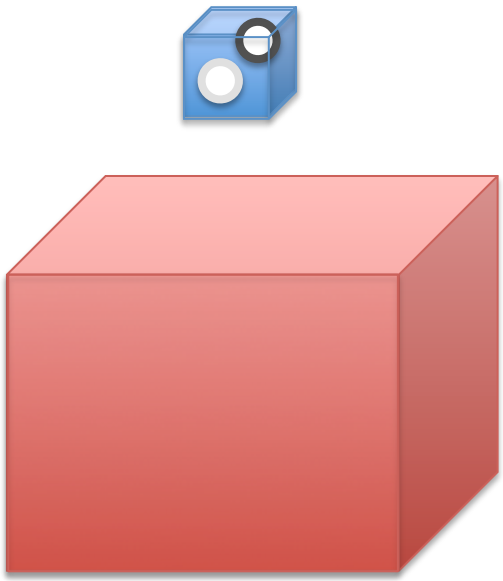
- OUR SETUP: Kinetically equilibrated heavy quarks

  presence of in-medium bound eigenstates?

  modern approach: Lattice QCD meson spectra



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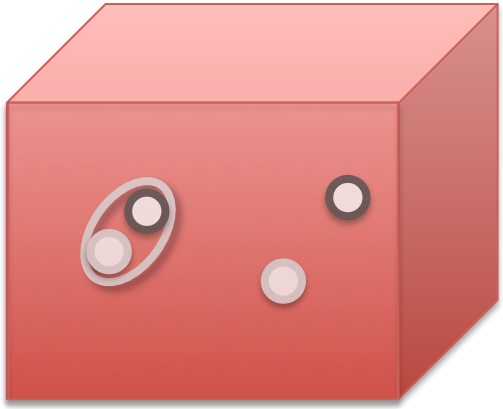

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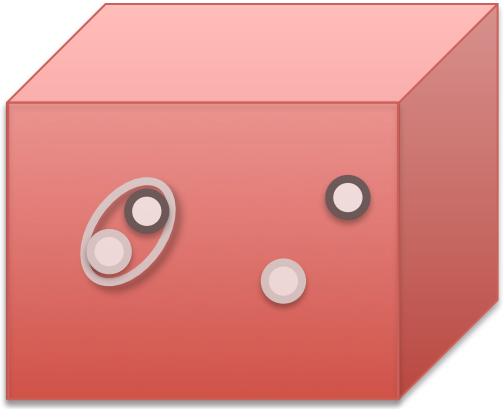

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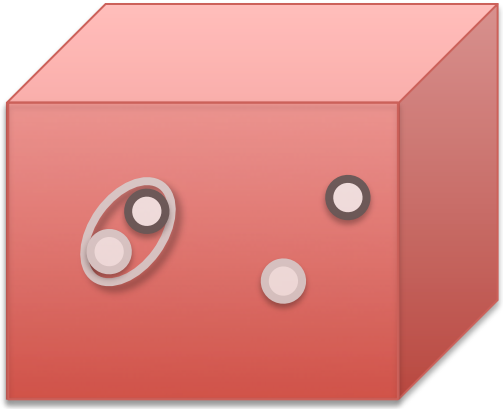

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Turn the separation of scales into an advantage: effective field theory NRQCD

Thacker, Lepage Phys.Rev. D43 (1991) 196-208

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Heavy quarks on the lattice

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Relativistic thermal field theory

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

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Relativistic thermal field theory

QCD

Dirac fields

$\bar{Q}(x), Q(x)$

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Relativistic thermal field theory

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

$$L_{NRQCD} = \chi^\dagger\left(iD_t + \frac{D_i^2}{2M_Q} + \ldots\right)\chi + \xi^\dagger(\ldots)\xi$$

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

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

well behaved for $nM_Q a \geq 3$

Davies, Thacker Phys.Rev. D45 (1992)

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- $^3S_1$ (J/ψ,Υ) and $^3P_1$ (χ_{c1}, χ_{b1}) channel correlators D(τ) from heavy quark propagators G(τ)

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

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T>0 QCD with N_f=2+1 HISQ flavors

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- Light d.o.f. (gluons, u d s quarks) represented by HotQCD configurations

A. Bazavov et. al., Phys. Rev. D 85 (2012) 054503

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HotQCD HISQ/tree action $48^3 \times N_\tau$ $m_{u,d}/m_s = 0.05$

β	6.664	6.700	6.740	6.770	6.800	6.840	6.880
$a[fm]$	0.1169	0.1130	0.1087	0.1057	0.1027	0.09893	0.09528
$M_b a$	2.759	2.667	2.566	2.495	2.424	2.335	2.249
$T/T_C(N_\tau = 12)$	0.911	0.944	0.980	1.008	1.038	1.078	1.119
β	6.910	6.950	6.990	7.030	7.100	7.150	7.280
$a[fm]$	0.09264	0.08925	0.086	0.08288	0.07772	0.07426	0.06603
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$T/T_C(N_\tau = 12)$	1.151	1.194	1.240	1.286	1.371	1.436	1.614

  - Important for the use with lattice NRQCD: **2.759 > M_ba > 1.559** (ok if n=2)
    0.757 > M_ca > 0.427 (ok if n>=6)

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  - Temperature changed by variation of the lattice spacing 140MeV < T < 249MeV

    For a study based on the fixed scale approach see: FASTSUM G. Aarts et. al. JHEP 1407 (2014) 097, JHEP 1111 (2011) 103

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  - Low temperature configurations available at b=6.664, 6.8, 6.95, 7.28 (48^3x32,64)

A Novel Bayesian Approach

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- 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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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]

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

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

  - No apriori restriction on the search space
  - Convergence to unique global extremum

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Bottomonium in lattice NRQCD

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

T=0 Bottomonium Correlators

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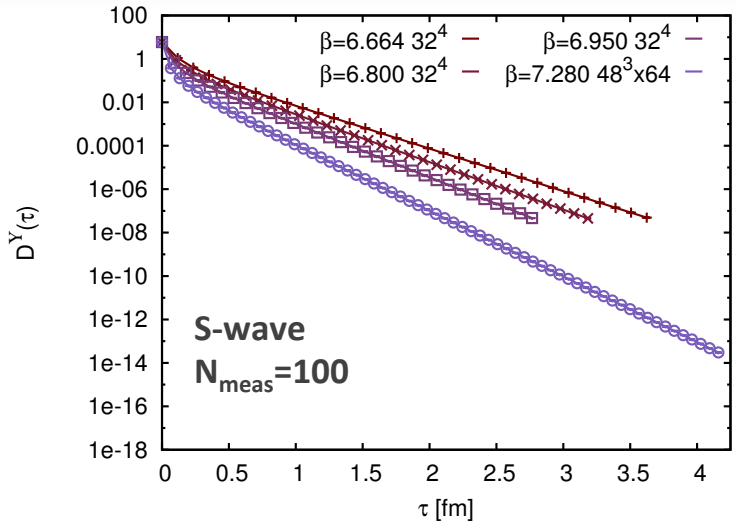

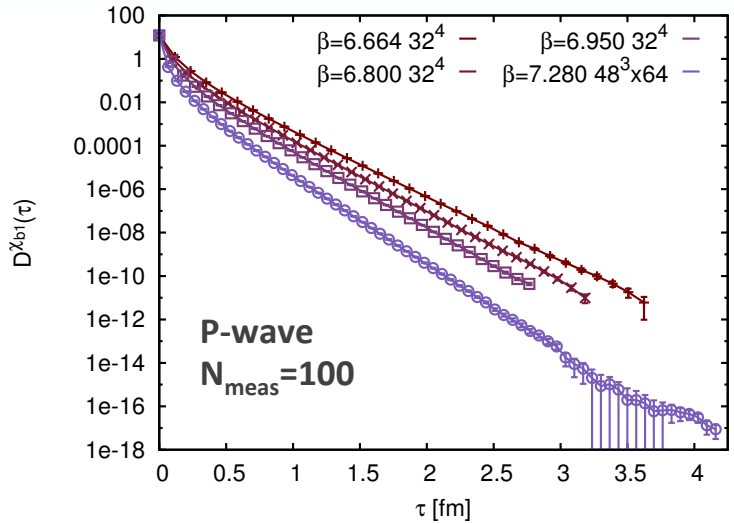

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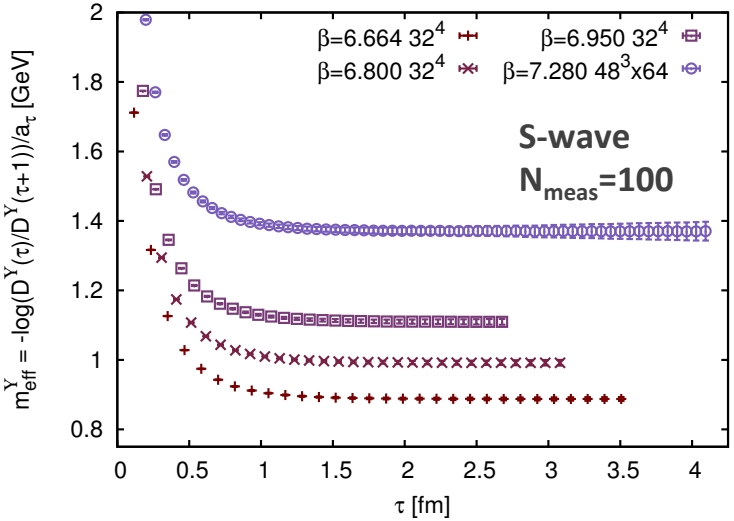

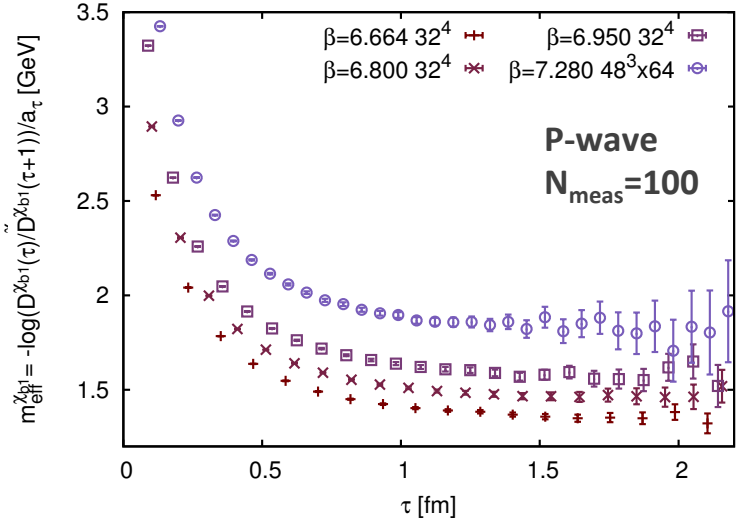

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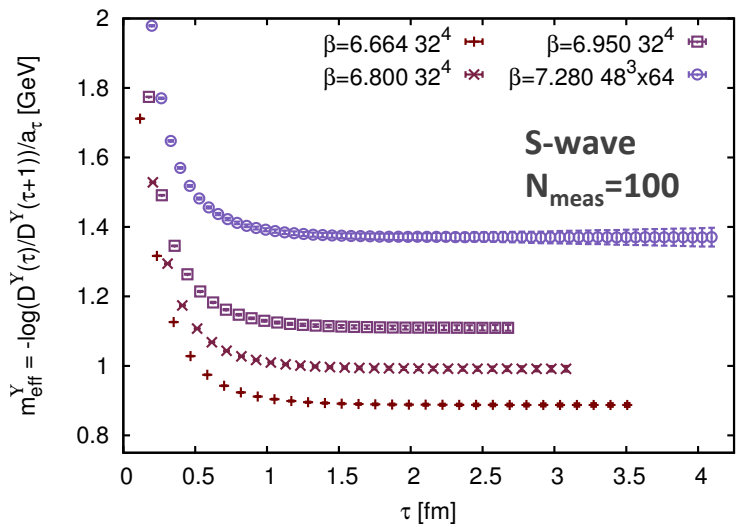

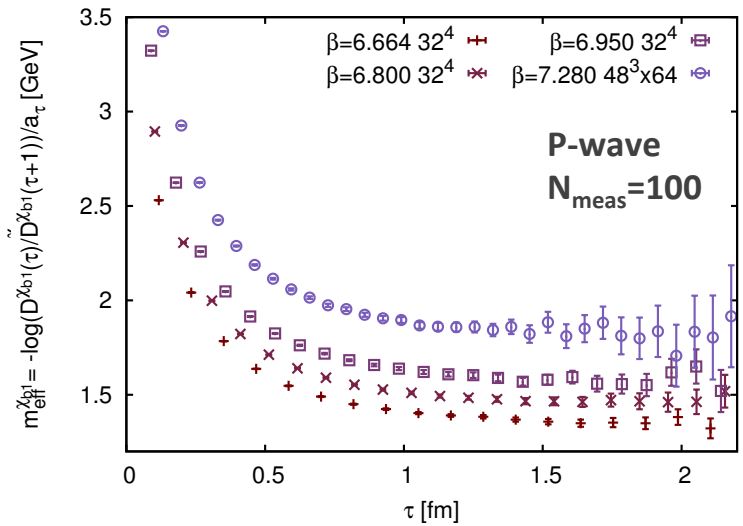

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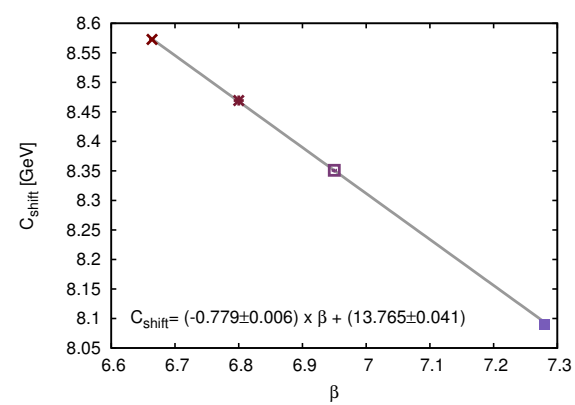
Phys.Rev. D 91 (2015) 054511

- "Integrating out M_b" induces energy shift of $\sim 2M_b$

$$M^{exp}_{\Upsilon(1S)} = M^{NRQCD}_{\Upsilon(1S)} + \boxed{2(Z_{M_b} M_b - E_0)}$$

$$M^{exp}_{\Upsilon(1S)} = 9.46030(26)\,\mathrm{GeV} \qquad C_{shift}(\beta)$$



T=0 Bottomonium Correlators

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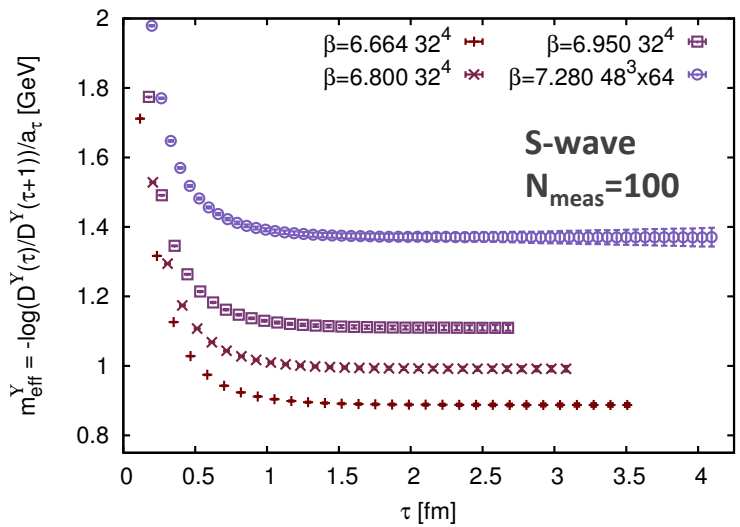

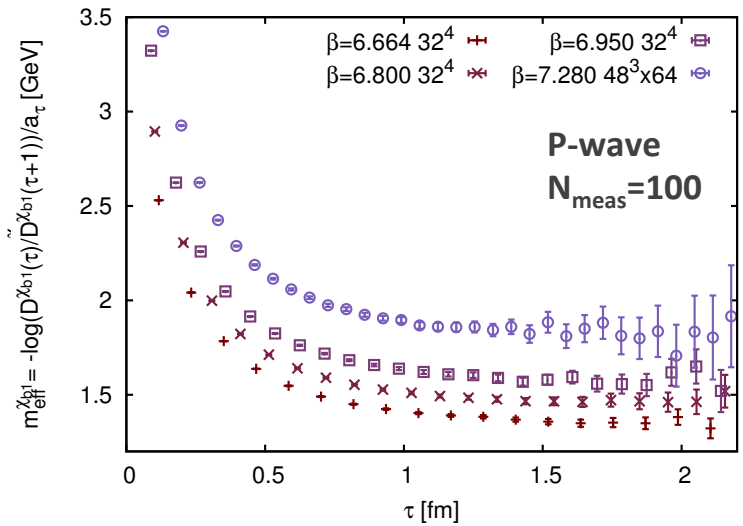

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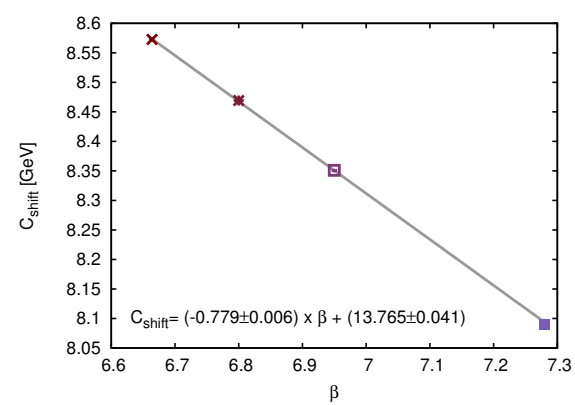

$$M_{\chi_{b1}(1P)} = M^{NRQCD}_{\chi_{b1}} + C(\beta) = 9.917(3)\,\mathrm{GeV} \;>\; M^{exp}_{\chi_{b1}(1P)} = 9.89278(26)(31)\,\mathrm{GeV}$$

T=0 Bayesian Bottomonium Spectra

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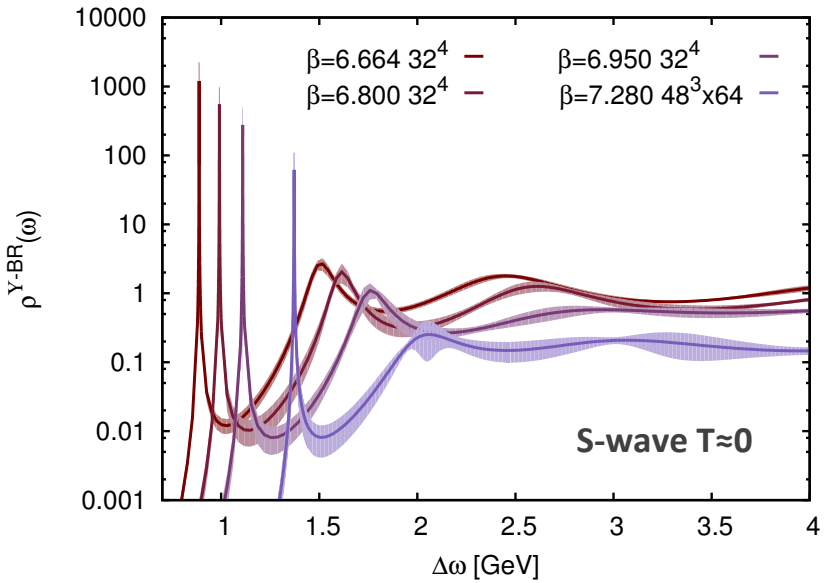

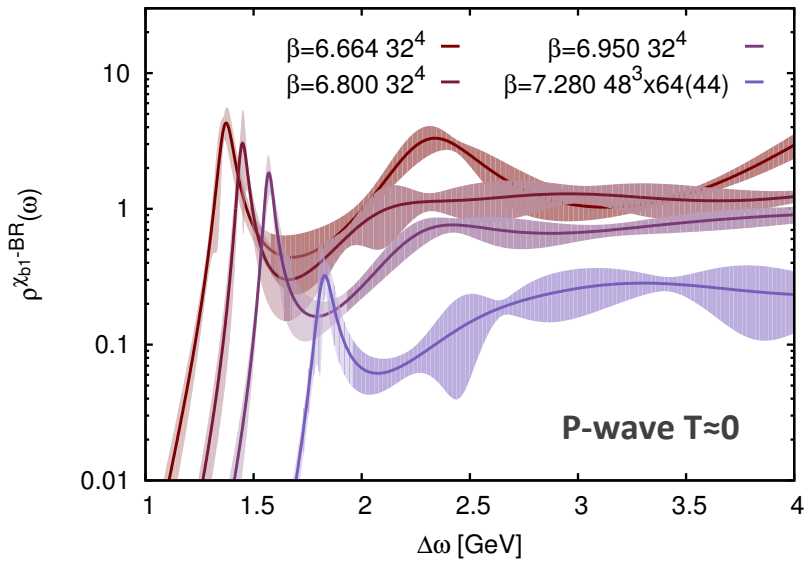

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T=0 Bayesian Bottomonium Spectra

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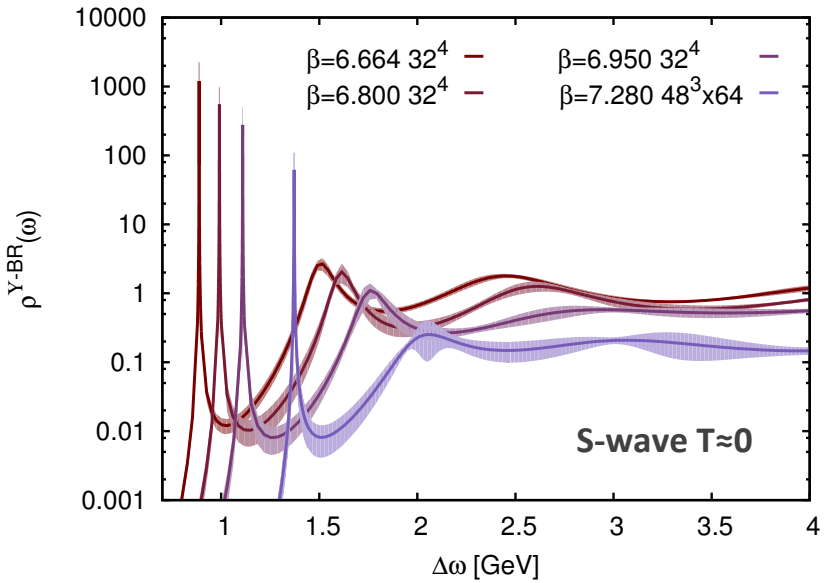

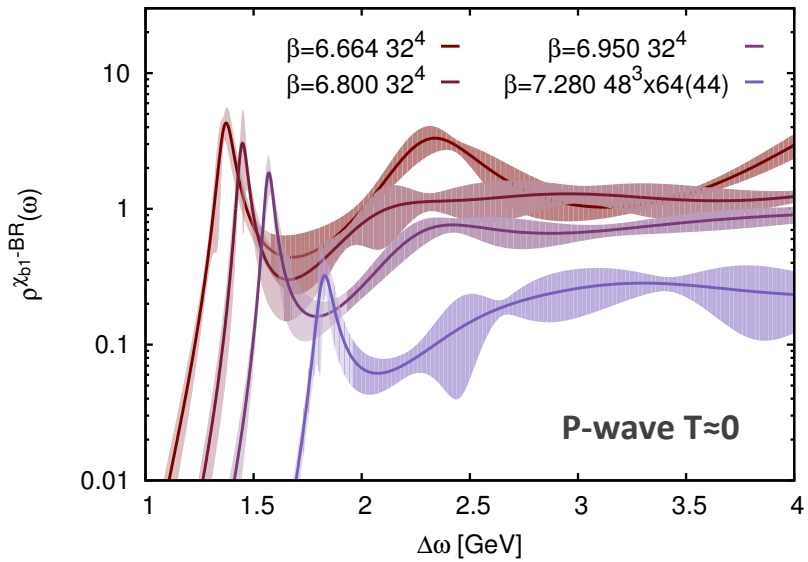

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T=0 Bayesian Bottomonium Spectra

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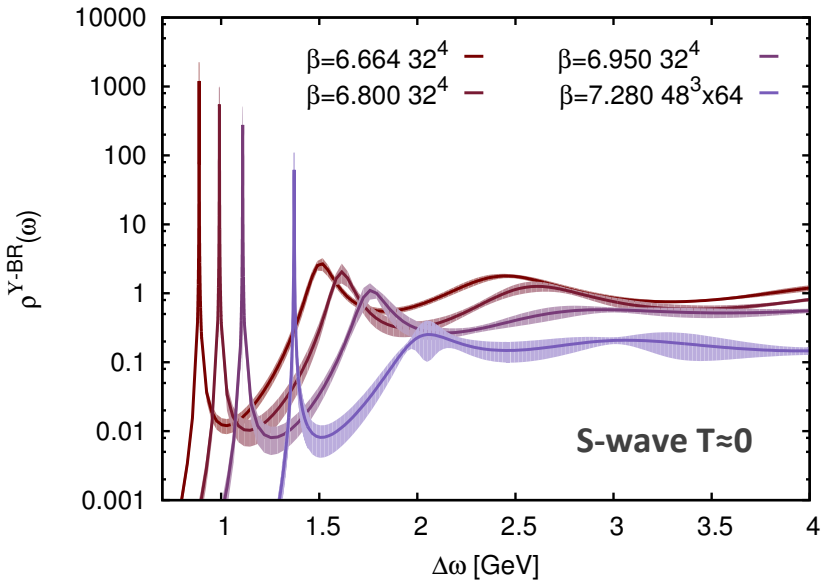

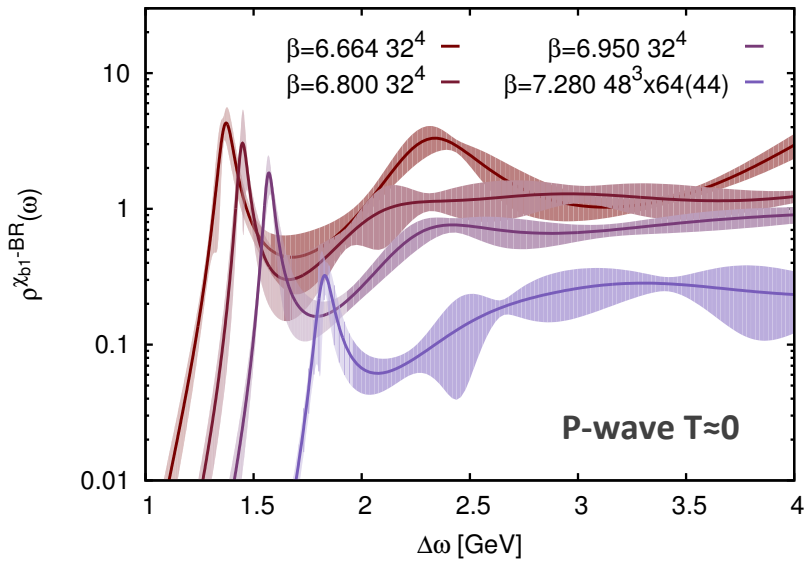

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- S-wave ground state peak very well resolved, next peak mostly from Υ(2S)
- P-wave ground state broader: worse s/n ratio and smaller physical peak size

Reconstruction Accuracy: S-wave

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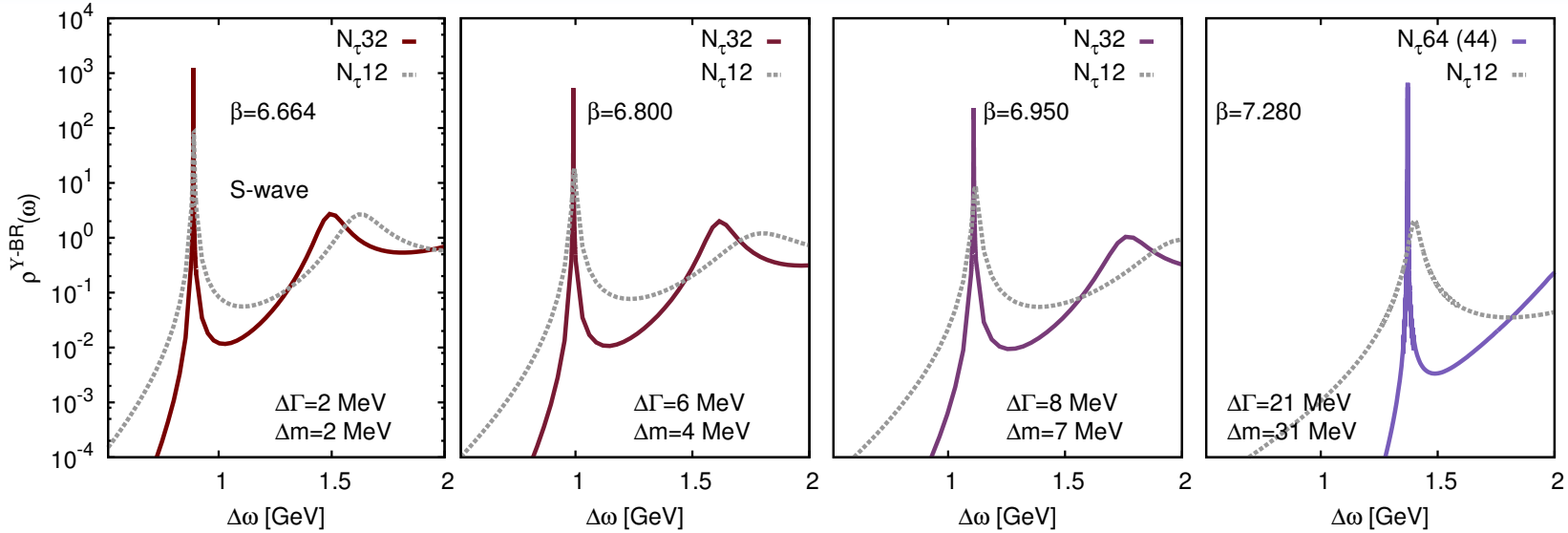

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- High precision of the improved Bayesian reconstruction (narrow width resolved)
- How does accuracy suffer from limited available information at T>0 (Nτ=12) ?
- One of the tests we ran: truncate T=0 dataset (Nτ=32/64) to Nτ=12

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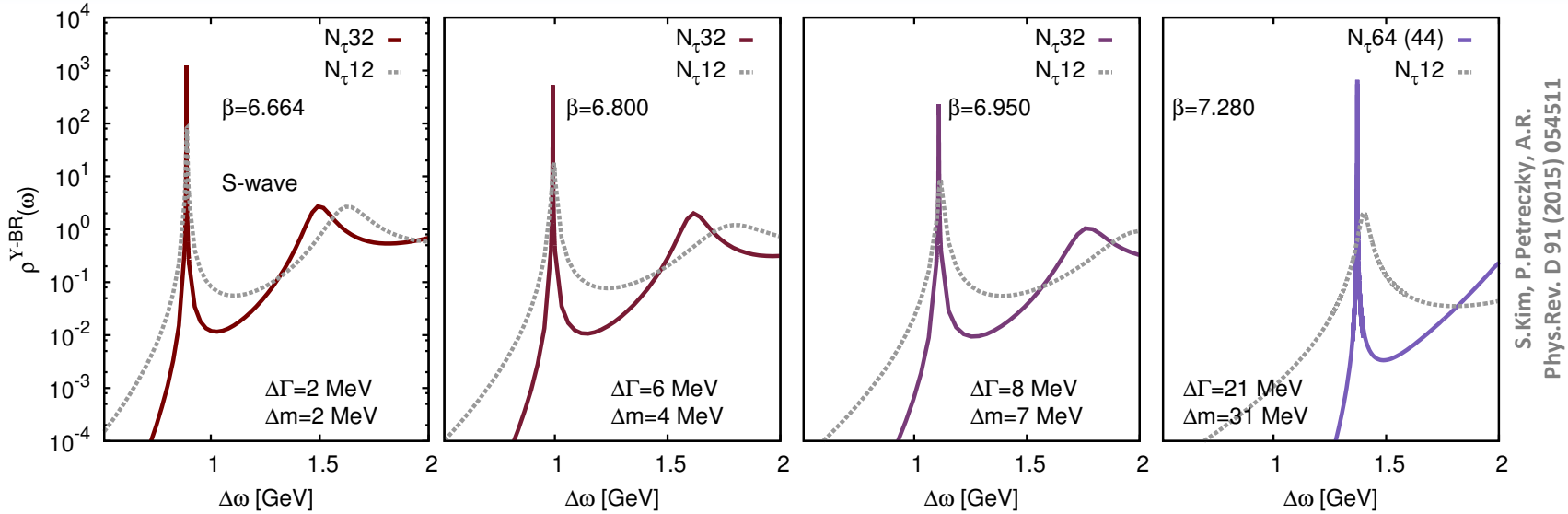

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Overall Limits:

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

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

Reconstruction Accuracy: P-wave

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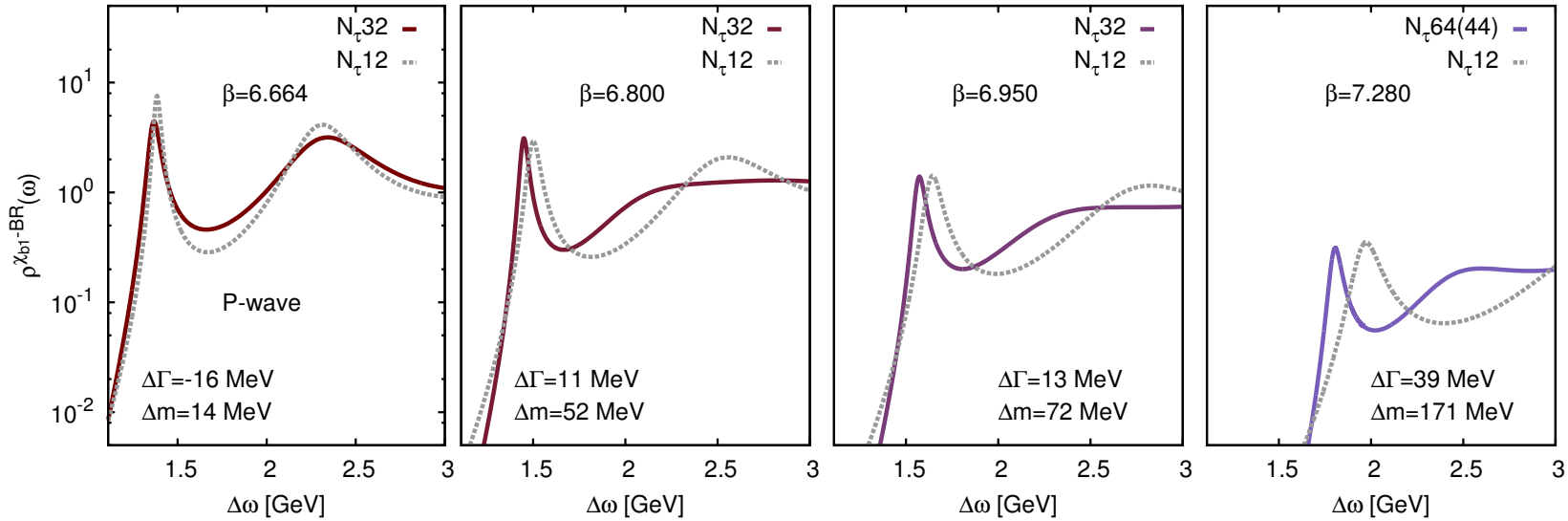

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- Estimate systematics: truncate T=0 dataset (Nτ=32/64) to Nτ=12
- Due to a worse signal-to noise ratio, effect in P-wave is larger than for S-wave

Overall Limits:

$$\beta = 6.664: \quad \Delta m_T < 60\text{MeV}, \quad \Delta\Gamma_T < 20\text{MeV}$$
$$\beta = 7.280: \quad \Delta m_T < 200\text{MeV}, \quad \Delta\Gamma_T < 40\text{MeV}$$

Bottomonium T>0 Correlators

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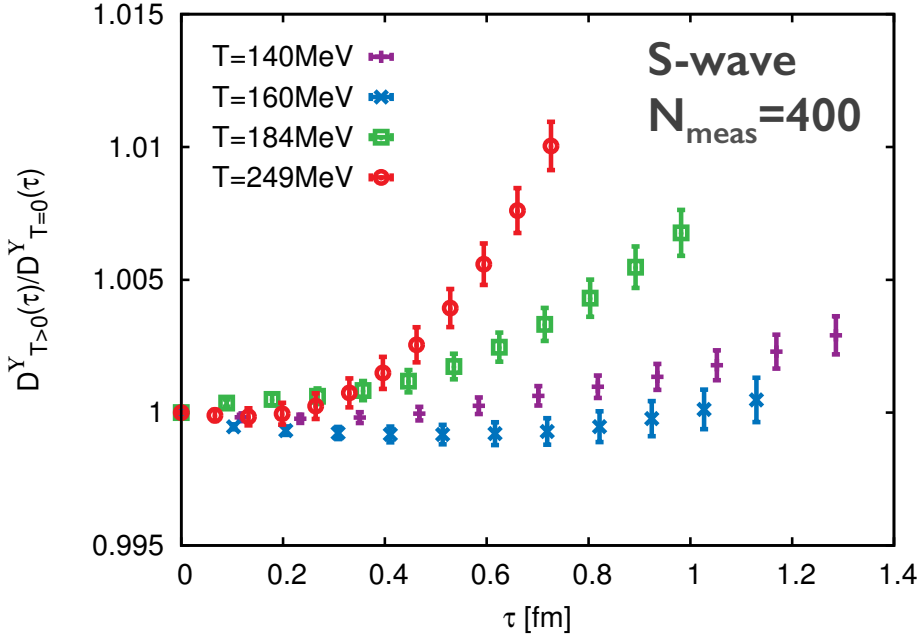
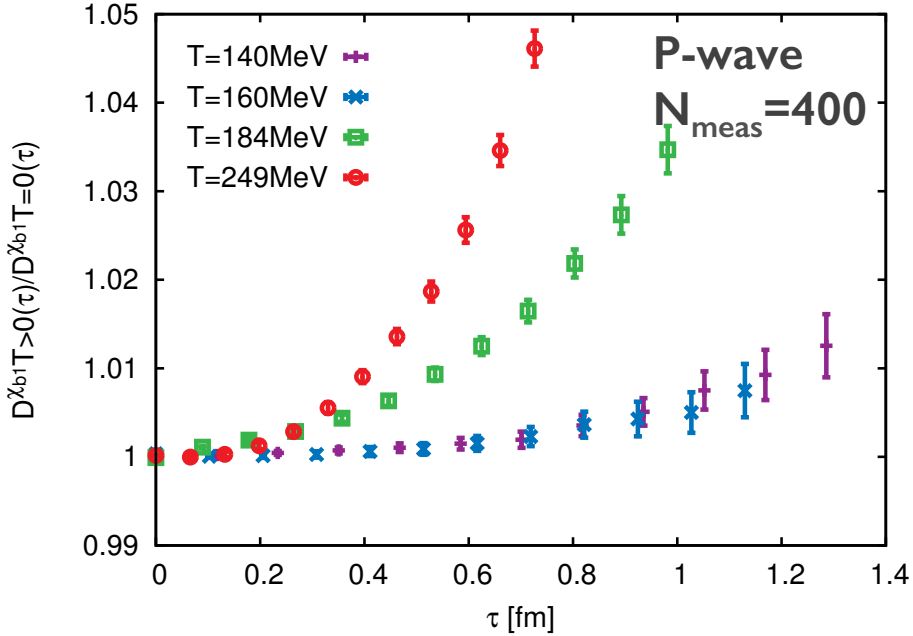


S-wave at most 1% change



P-wave at most 5% change

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- Statistically significant in-medium modification above T=160MeV
- Larger spatial extend makes P-wave more susceptible to medium

Spectral Functions At T>0

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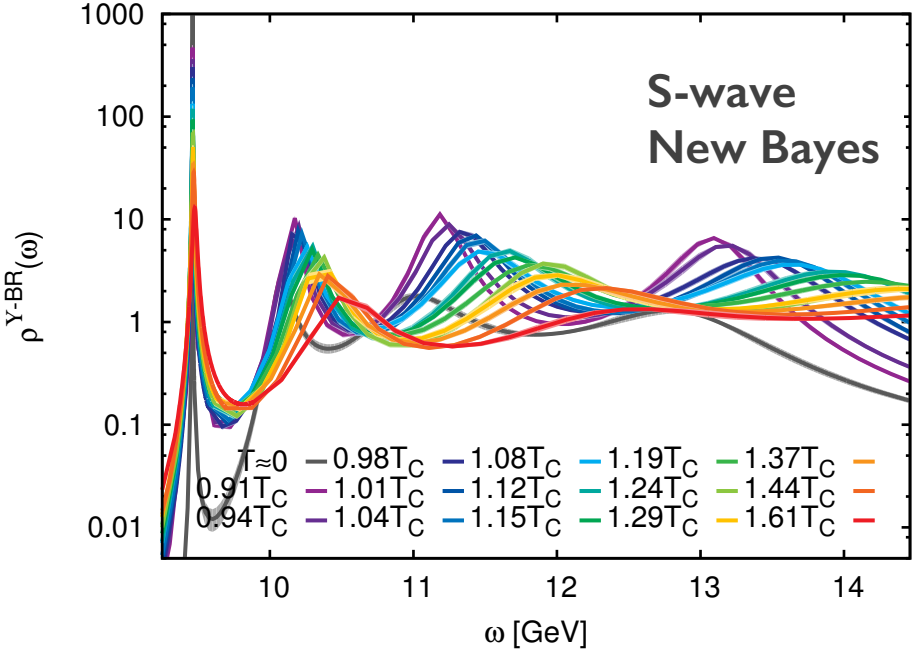

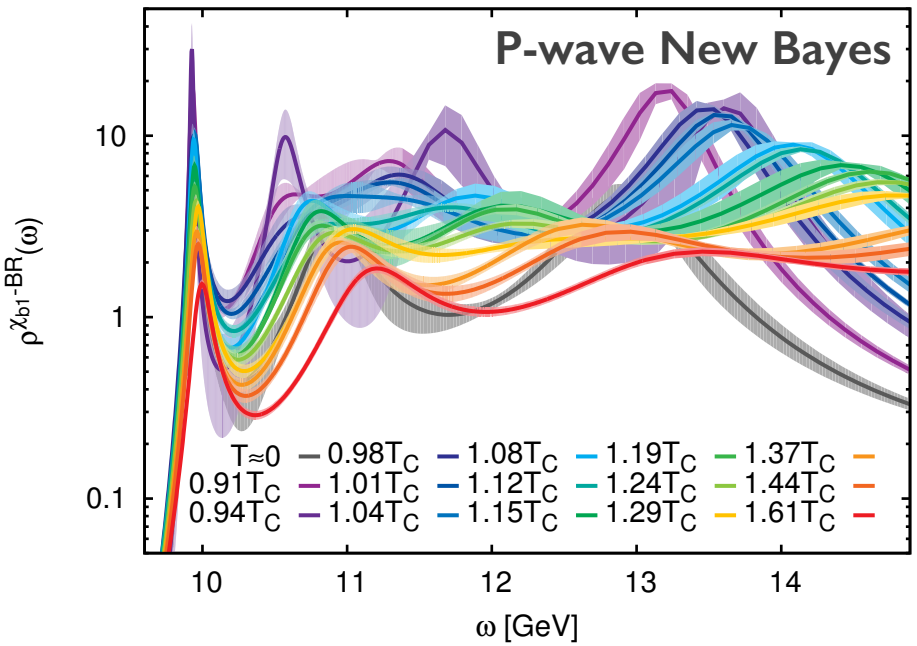

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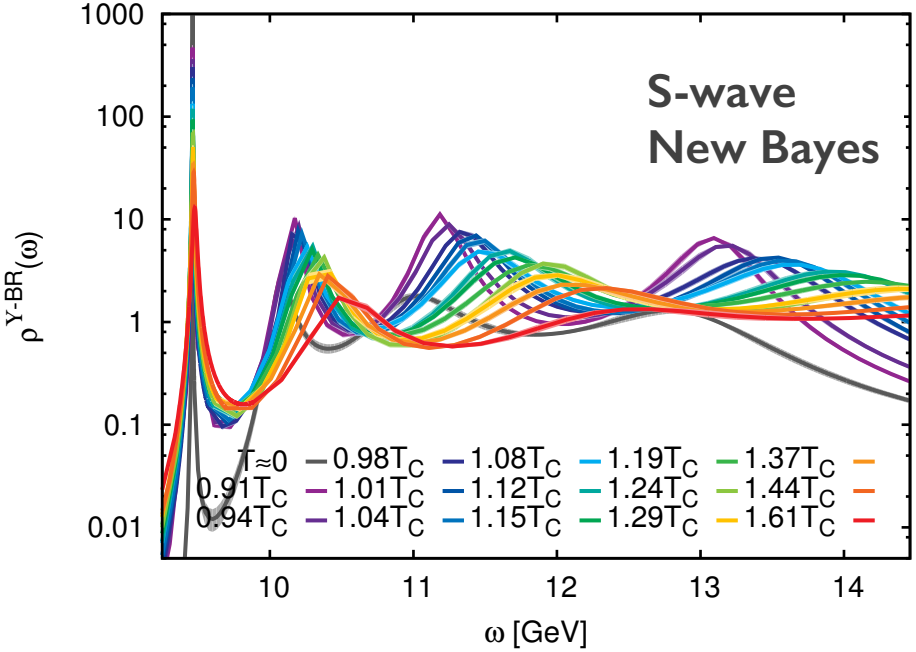

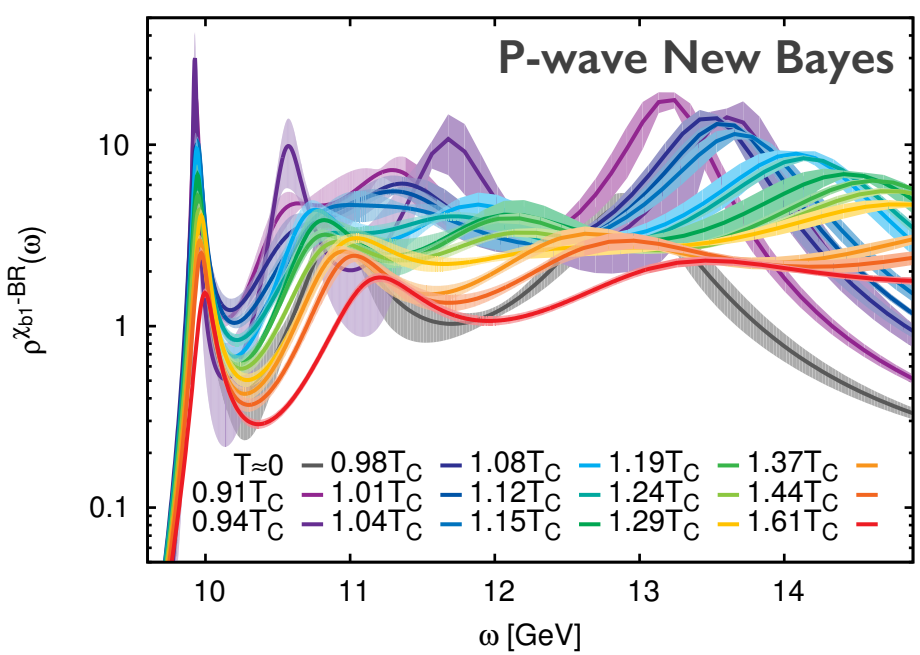

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- Naïve inspection by eye inconclusive: ground state peak present up to 1.61T_C ?

S- & P-wave Survival At T=249MeV

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

S- & P-wave Survival At T=249MeV

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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

S- & P-wave Survival At T=249MeV

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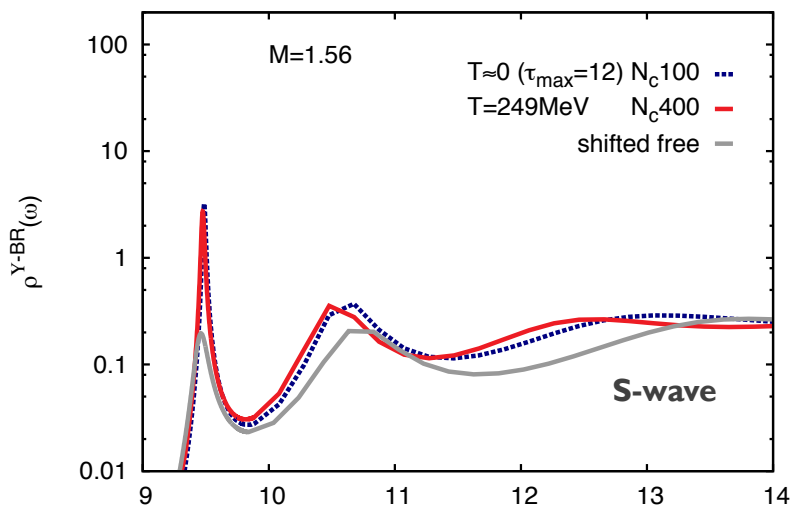

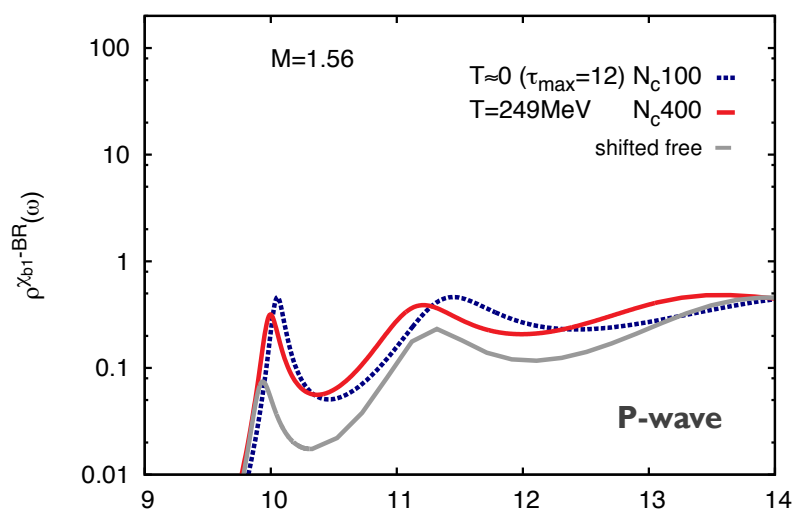

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- At T=249 MeV: Ground state peak still stronger than numerical ringing

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Towards Charmonium in lattice NRQCD

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T=0 Charmonium Correlators

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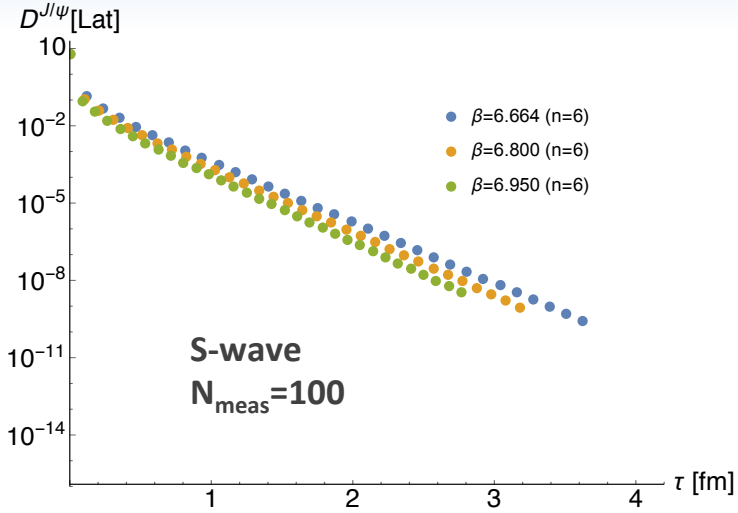

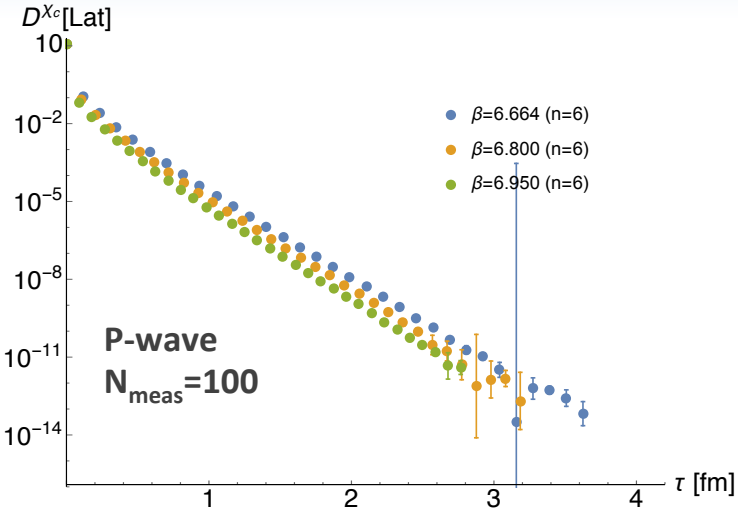

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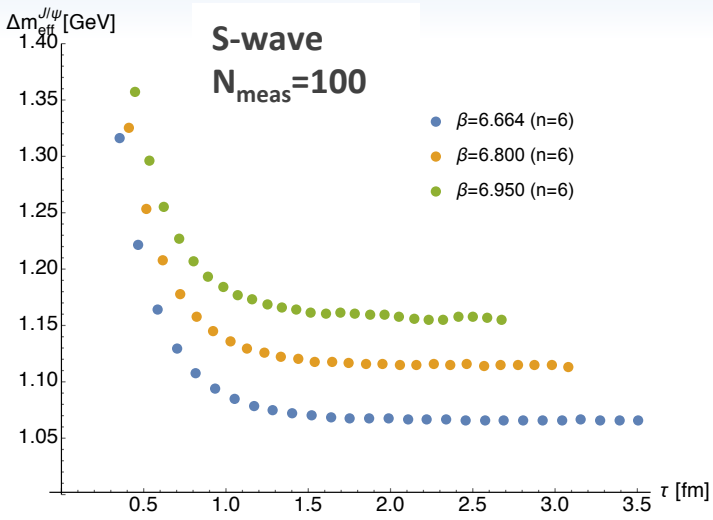

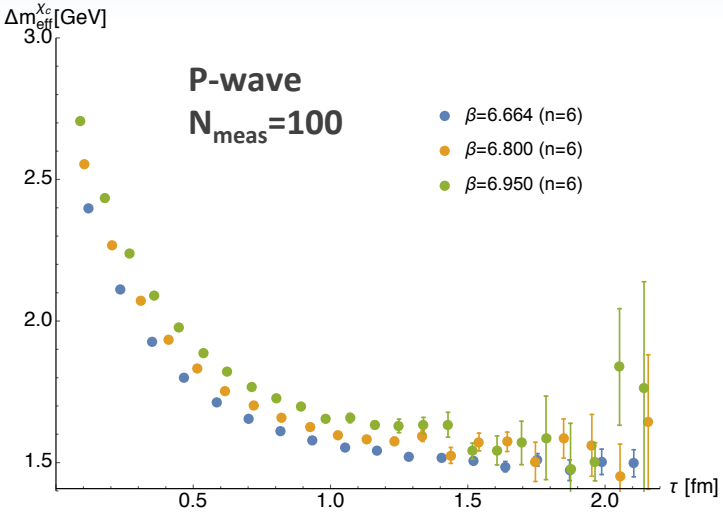

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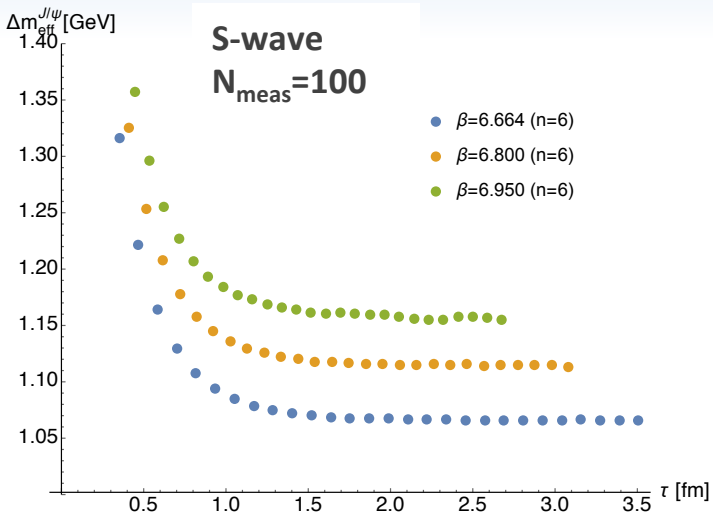

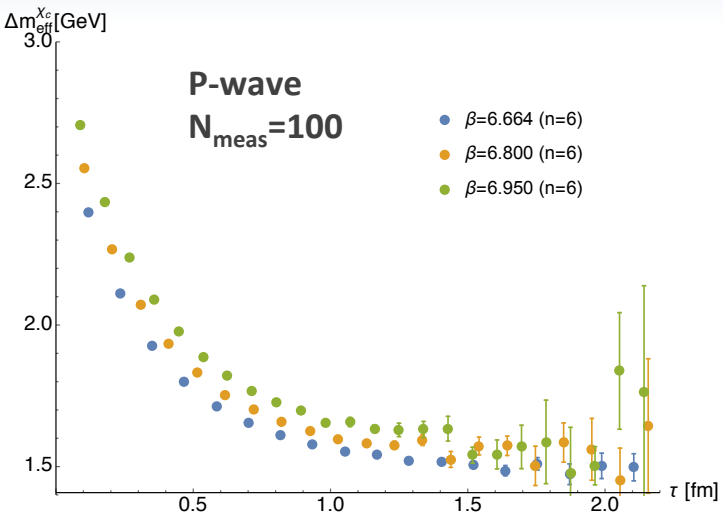

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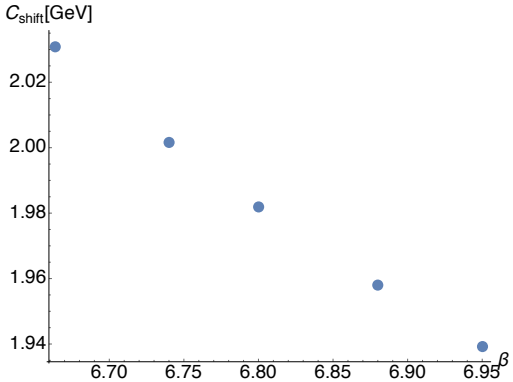
$$C_{shift}(\beta)$$



T=0 Charmonium Correlators

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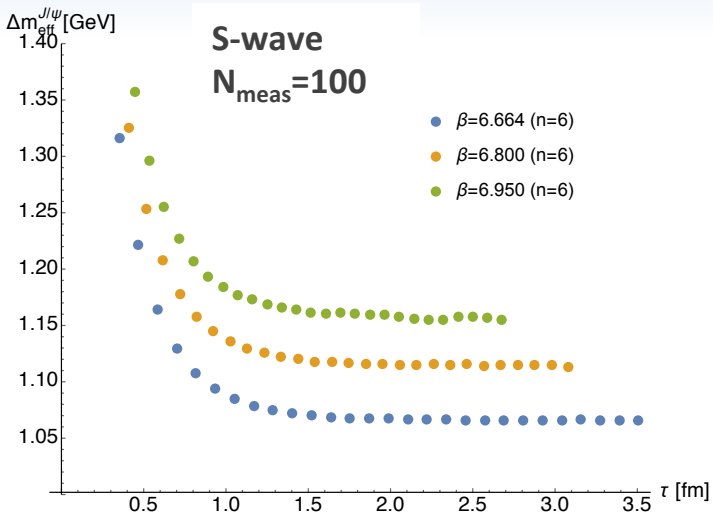

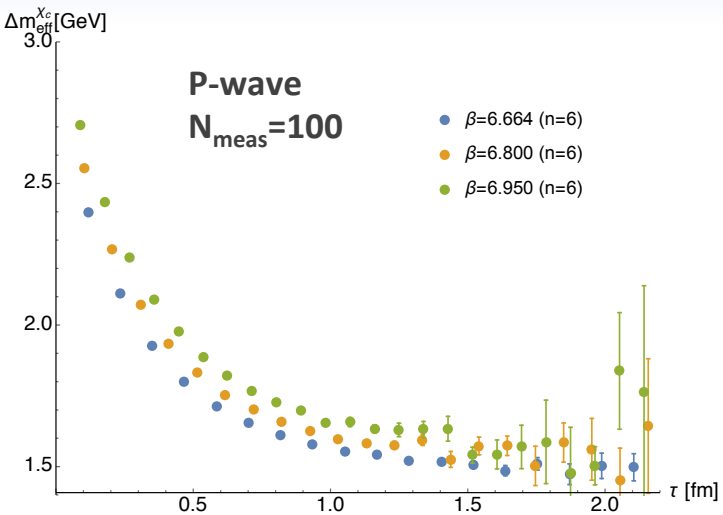

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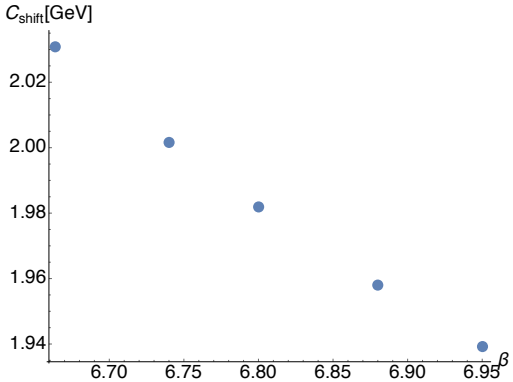

$$M_{\chi_{c1}} = M_{\chi_{c1}}^{NRQCD} + C(\beta) = 3.546(4)\,GeV \qquad M_{\chi_{c1}}^{exp} = 3.51066(7)\,GeV$$

Charmonium T>0 Correlators

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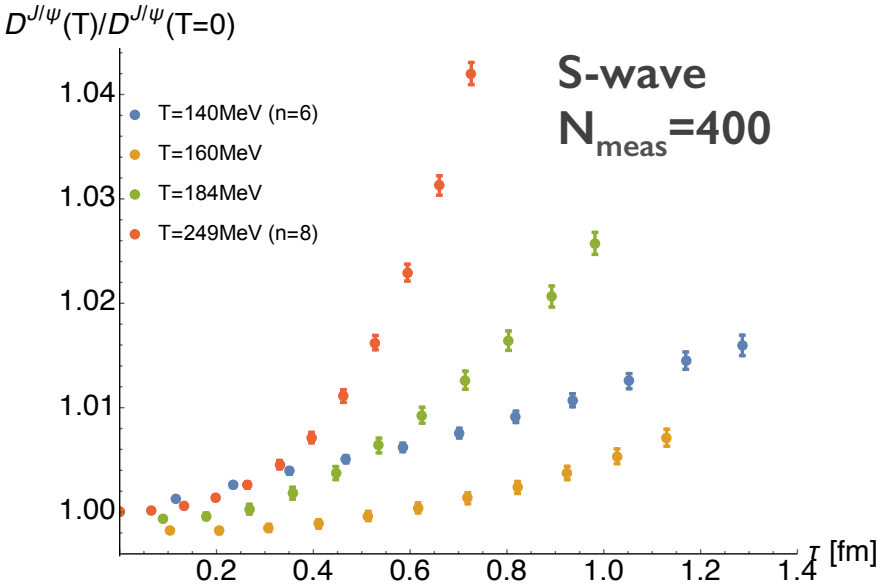

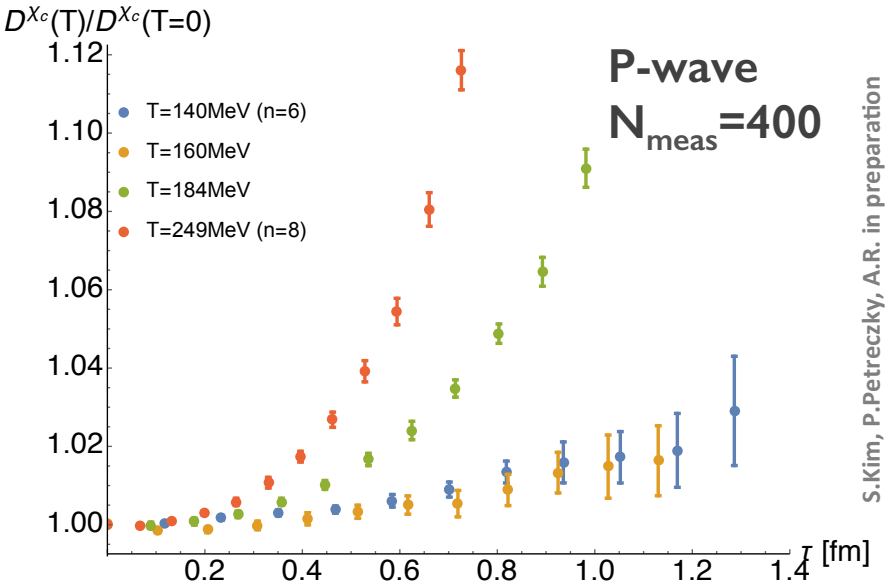

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S-wave at most ~5% change

P-wave at most ~12% change

- At $T=T_C$ J/ψ shows as much change as Υ at 249MeV
- While signal/noise worse for P-wave, in-medium modification at $T=T_C$

Charmonium At T=140MeV

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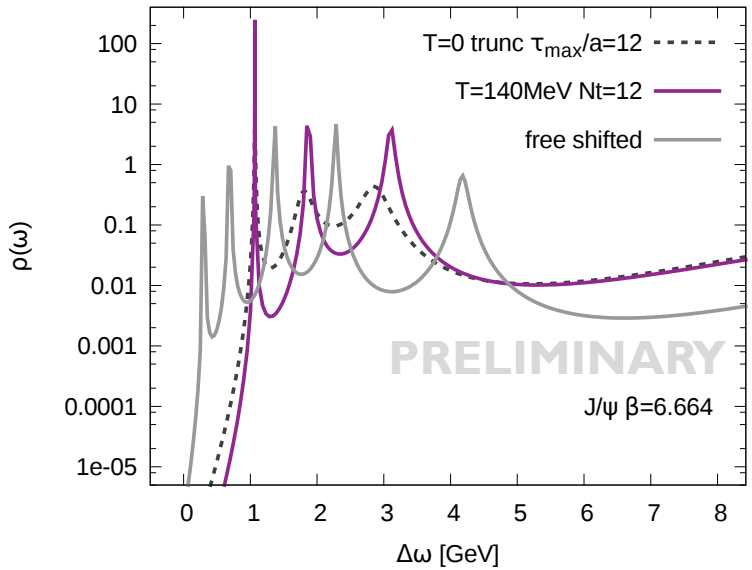
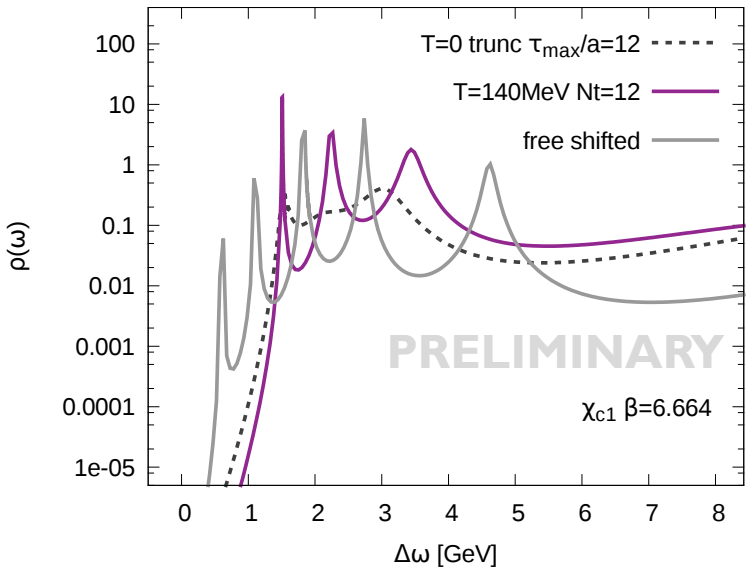
- Comparison between interacting and free spectral functions





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In preparation

- J/ψ peak clearly visible, χ_c signal marginal but present: survival of S- and P-wave

Conclusions

- Quarkonium is a precision probe of the QGP produced in heavy-ion collisions

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- Bottomonium from NRQCD in a realistic thermal medium (HISQ - HotQCD)
  - In-medium modification of correlators above T=160MeV [up to 1% (Υ) and 5% (χ_{b1})]
  - N_τ=12 datapoints allow us to set upper bounds on in-medium modification
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- Combined EFT and lattice QCD approach (latticeNRQCD): efficient and accurate
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Thank you for your attention