

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Bottomonium in NRQCD at T>0

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in collaboration with
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arXiv:1409.3630



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Bottomonium in Heavy-Ion Collisions



- At RHIC and LHC: Precision era of relativistic heavy-ion collision experiments

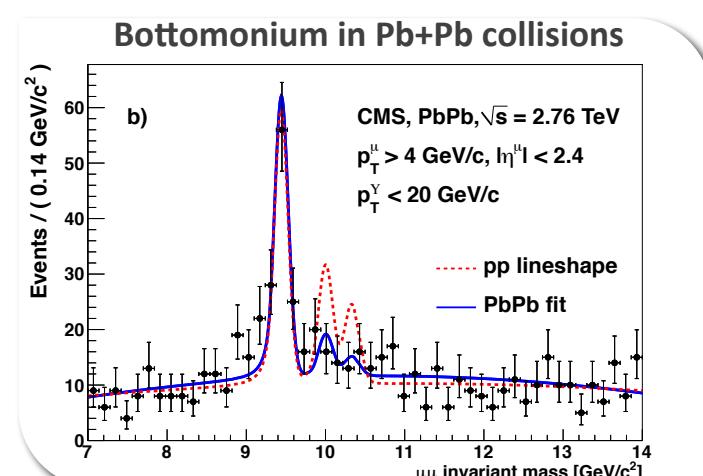
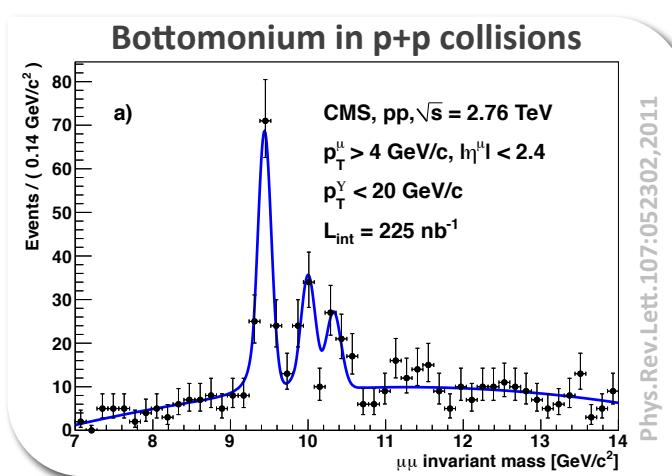
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(T_{LHC} from M. Wilde, Nucl. Phys. A 904-905, 573c (2013))

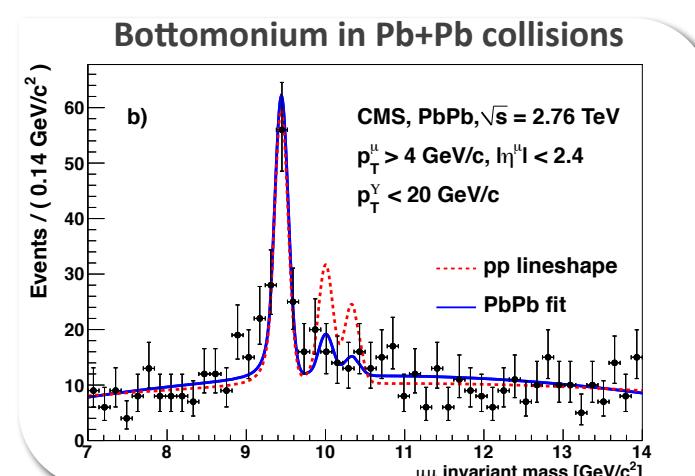
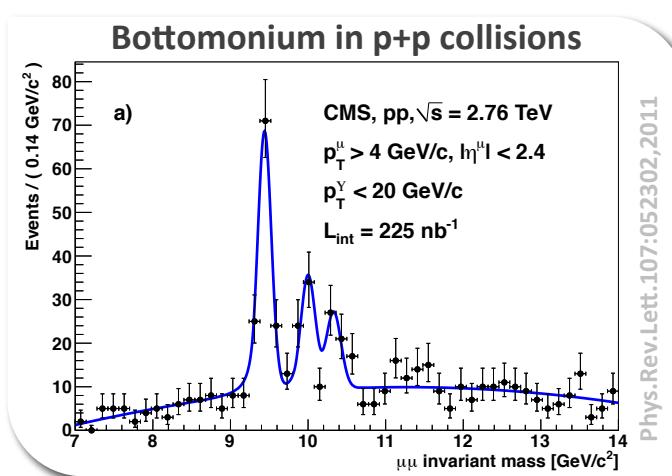
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- How to understand $b\bar{b}$ suppression in a strongly coupled QGP: lattice NRQCD
 started by J. Fingberg, Phys. Lett. B 424 (1998) 343, recently: FASTSUM G. Aarts et. al. JHEP 1407 (2014) 097, JHEP 1111 (2011) 103

Effective Field Theory: Lattice NRQCD



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

Heavy quark ψ and antiquark ξ as separate non-relativistic Pauli spinors

Light medium d.o.f. from a fully relativistic lattice simulation

Lepage et.al, Phys.Rev. D46 (1992) 4052-4067
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- Individual Q or anti-Q in a medium background: Initial value problem $G(\tau) = \langle \psi(\tau) \psi^\dagger(0) \rangle$

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

well behaved if $M_Q a > 1.5$
Davies, Thacker Phys.Rev. D45 (1992)



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

$$D(\tau) = \sum_x \langle O(x, \tau) G_{x\tau} O^\dagger(x_0, \tau_0) G_{x\tau}^\dagger \rangle_{\text{med}} \quad O({}^3S_1; x, \tau) = \sigma_i, \quad O({}^3P_1; x, \tau) = \Delta_i^\leftrightarrow \sigma_j - \Delta_j^\leftrightarrow \sigma_i$$

Thacker, Lepage Phys.Rev. D43 (1991)



A Medium With Nf=2+1 Light HISQ Flavors

- 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 × N _τ	$m_{u,d}/m_s = 0.05$			
β	6.664	6.700	6.740	6.770	6.800	6.840
a[fm]	0.1169	0.1130	0.1087	0.1057	0.1027	0.09893
M _b a	2.759	2.667	2.566	2.495	2.424	2.335
T/T _C (N _τ = 12)	0.911	0.944	0.980	1.008	1.038	1.078
β	6.910	6.950	6.990	7.030	7.100	7.150
a[fm]	0.09264	0.08925	0.086	0.08288	0.07772	0.07426
M _b a	2.187	2.107	2.030	1.956	1.835	1.753
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fixed scale approach by 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



A Novel Bayesian Spectral Reconstruction

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

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

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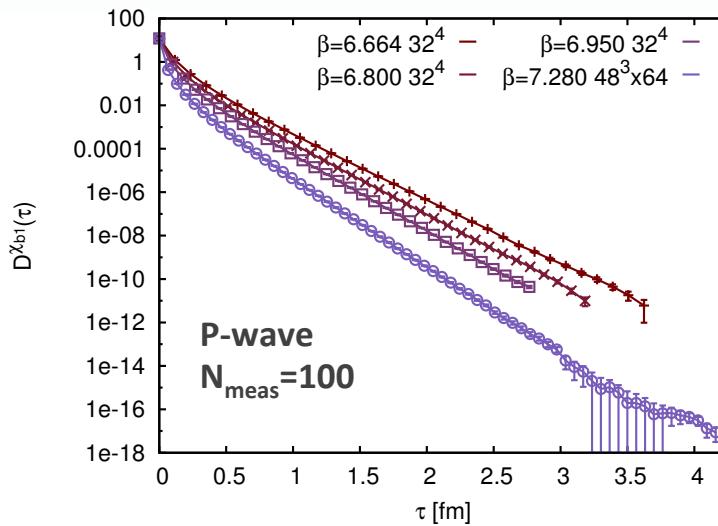
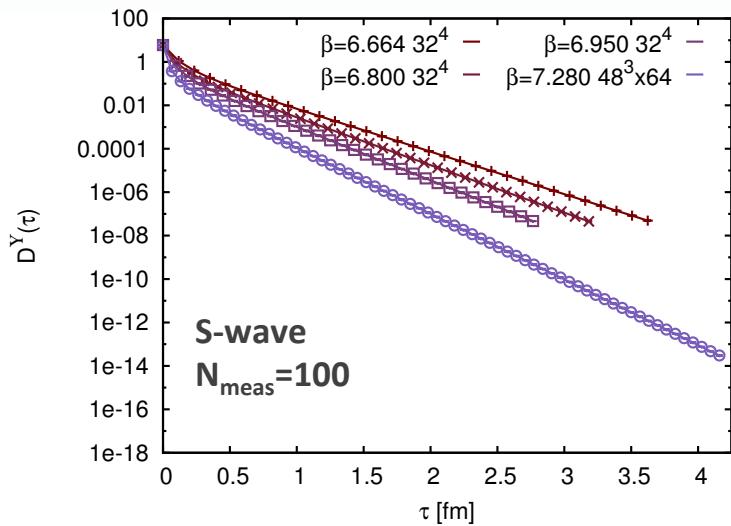
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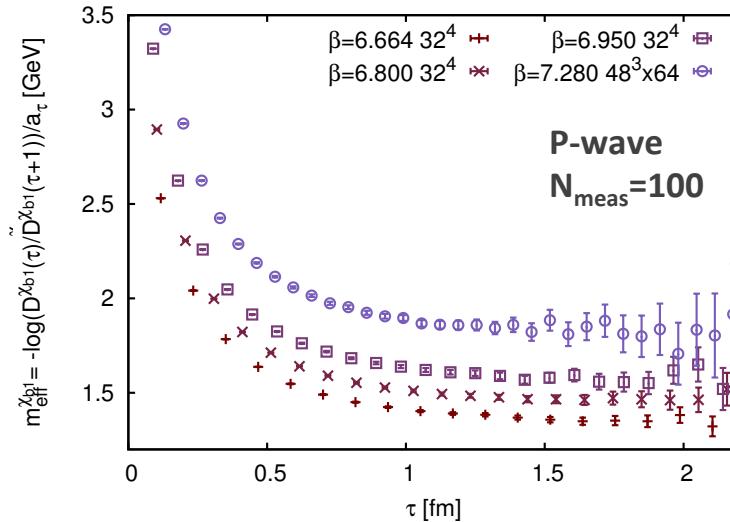
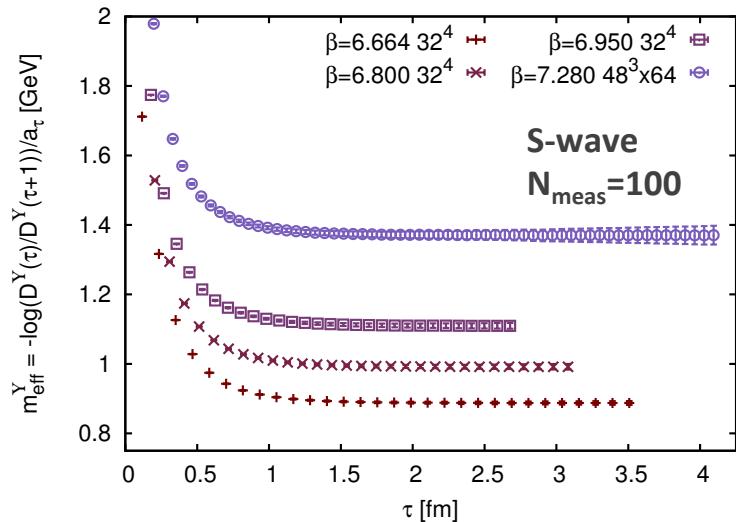
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$$\frac{\delta}{\delta \rho} P[\rho|D, I] \Big|_{\rho=\rho^{BR}} = 0$$

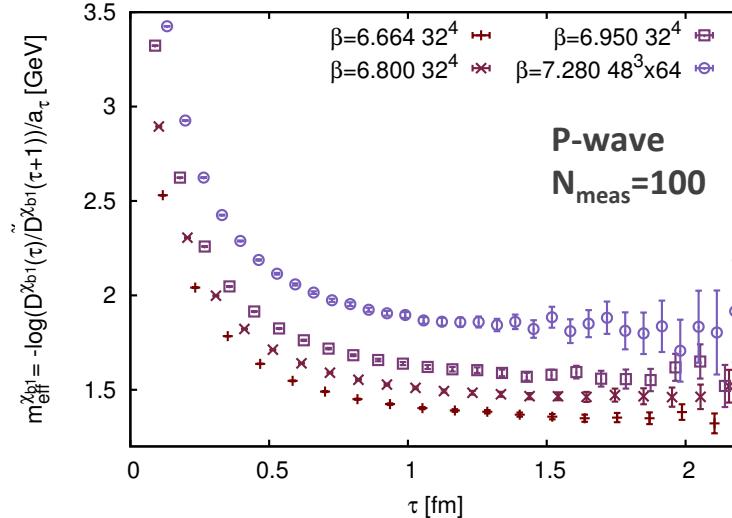
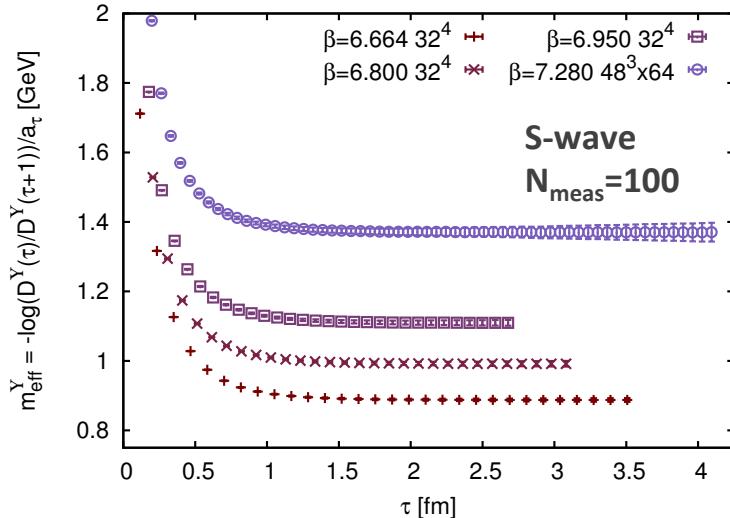
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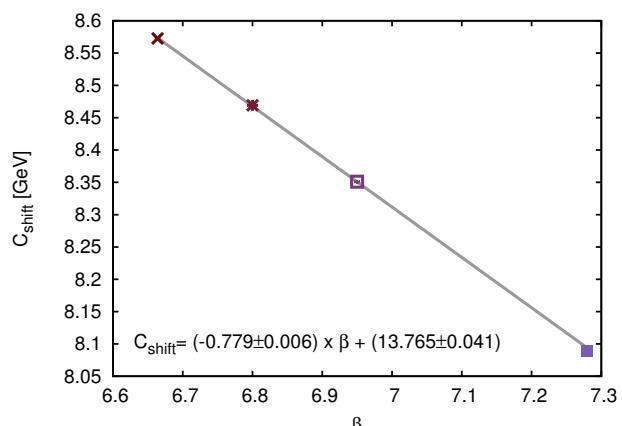
S.Kim, P.Petreczky, A.R. arXiv:1409.3630

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

$$M_{\gamma(1S)}^{\text{exp}} = M_{\gamma(1S)}^{\text{NRQCD}} + 2(Z_{M_b} M_b - E_0)$$

$$M_{\gamma(1S)}^{\text{exp}} = 9.46030(26) \text{ GeV}$$

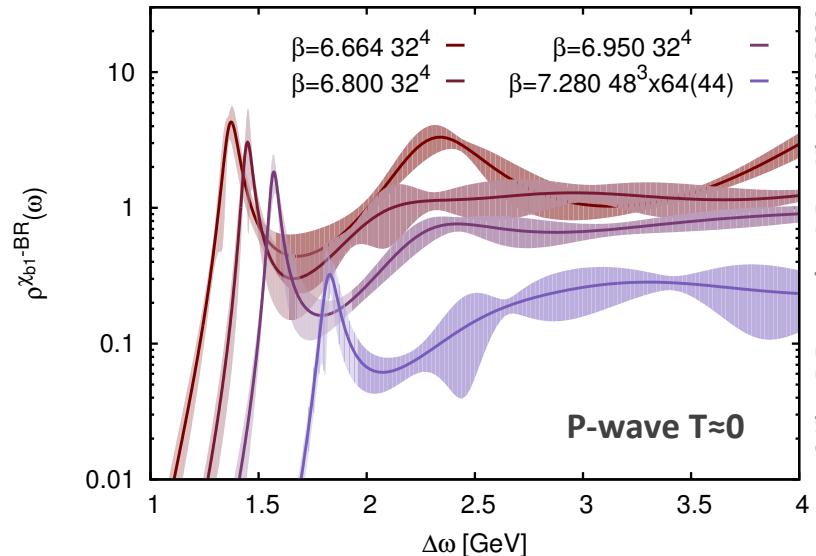
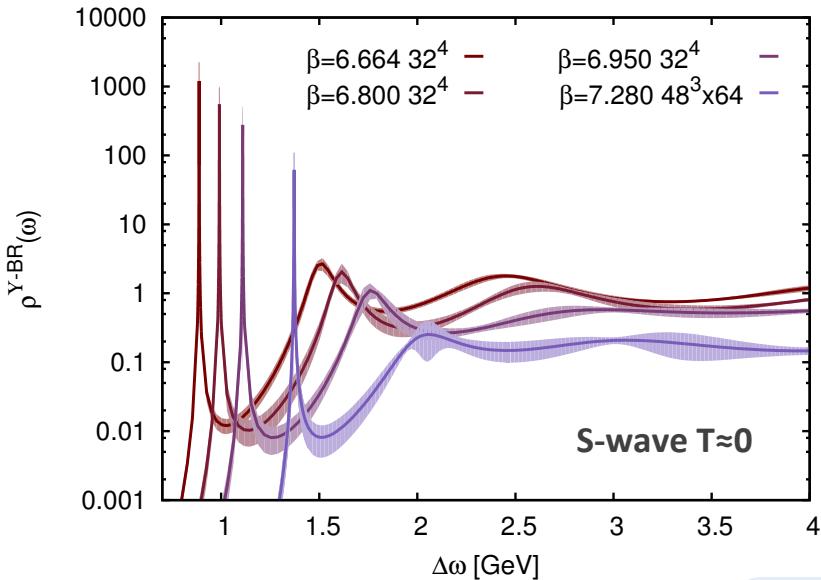
$$C_{\text{shift}}(\beta)$$



- Linear dependence: interpolated values to calibrate mass shift at intermediate β



Spectral Functions Close To T=0

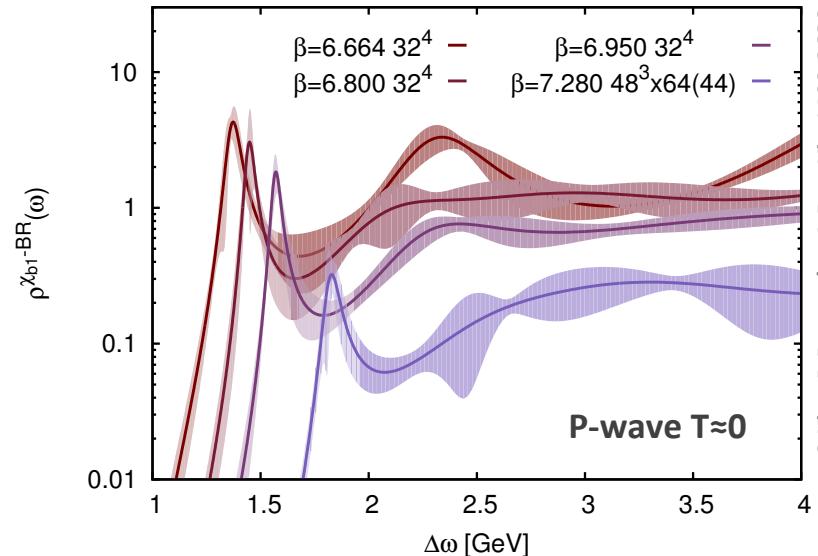
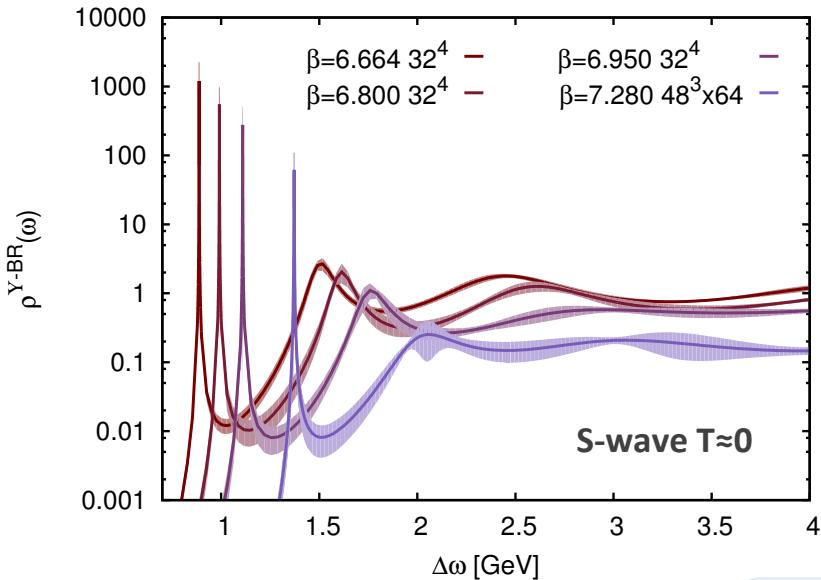


■ Bayesian reconstruction:

$N_\omega = 1200$ $I_\omega = [-0.5, 30]$ $\beta^{\text{num}} = 20$ $N_{\text{jack}} = 10$
 $m_l = \text{const}$, 512 bit precision, $\Delta\text{tol} = 10^{-60}$



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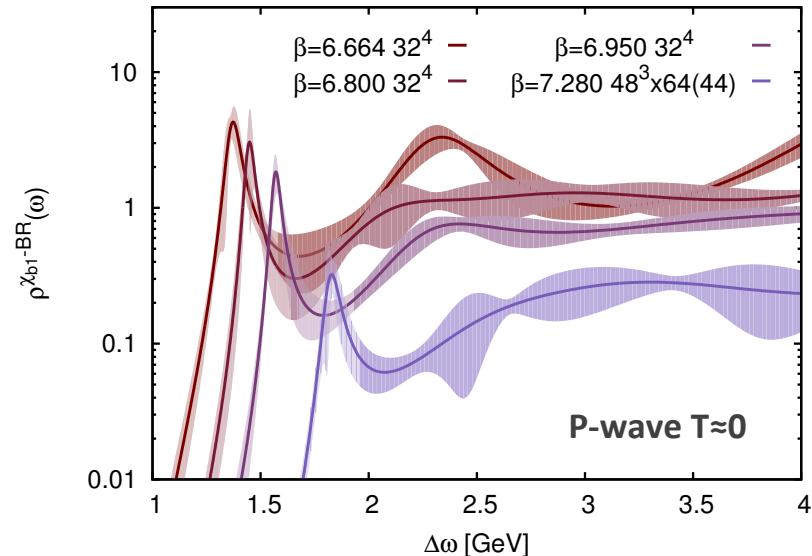
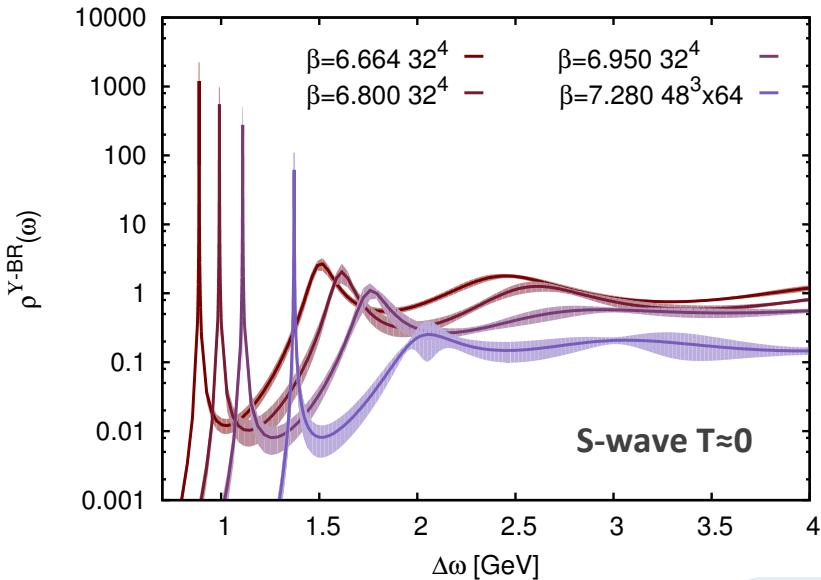
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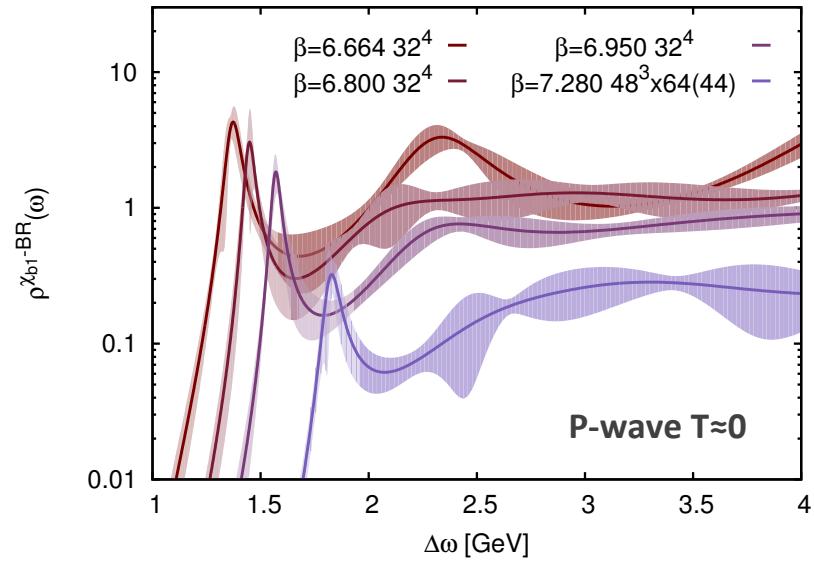
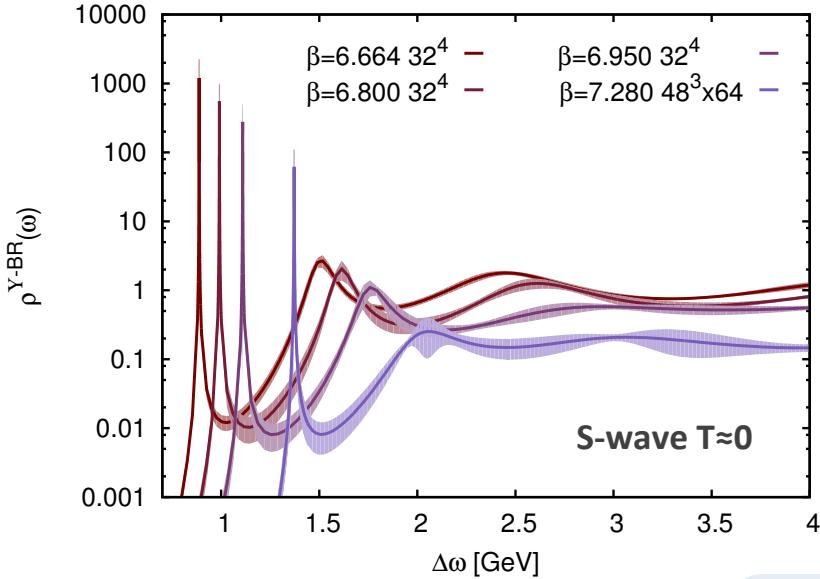
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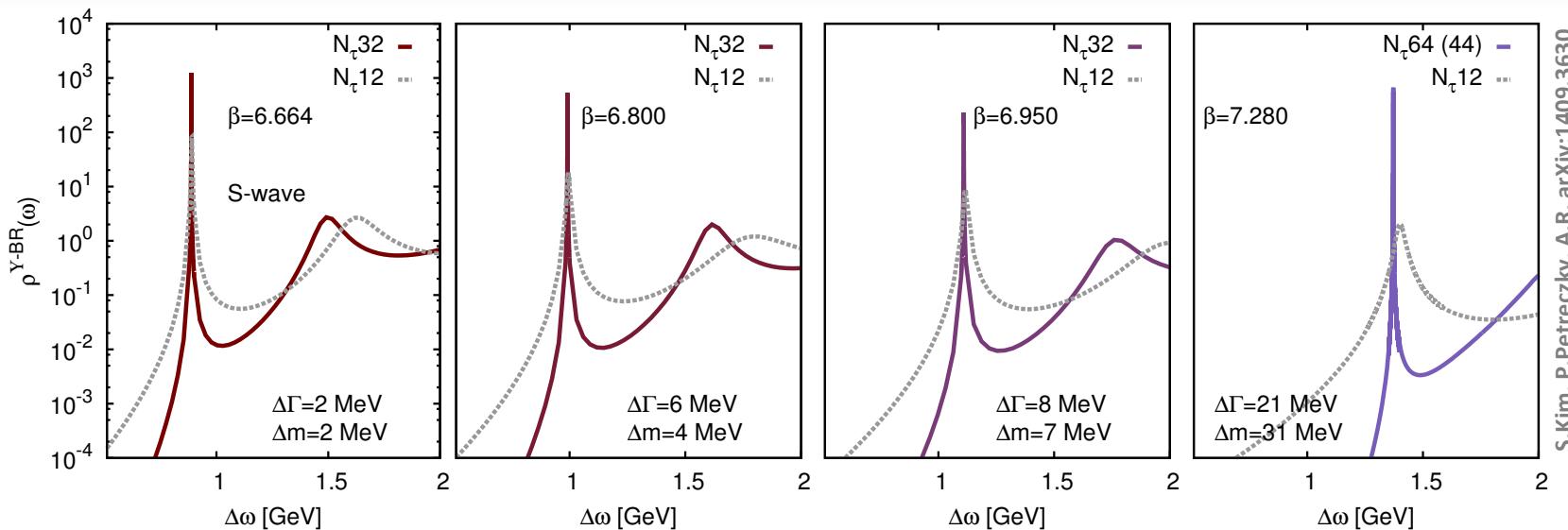
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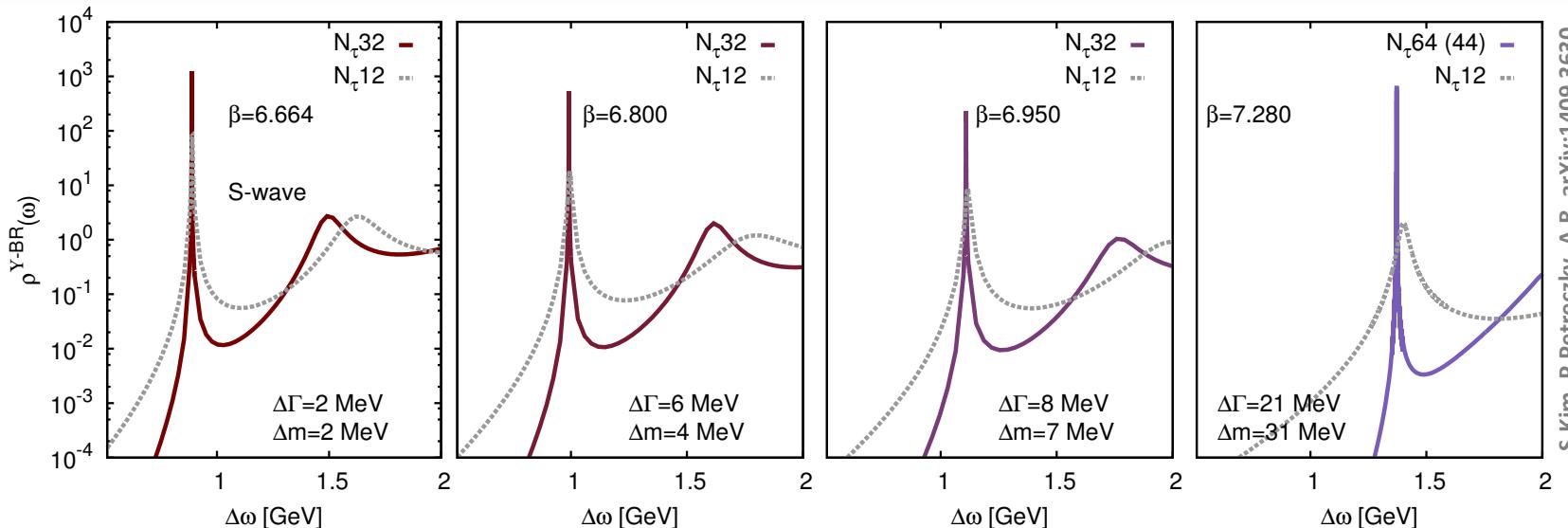
$$M_{\chi_{b1}(1P)} = M_{\chi_{b1}}^{\text{NRQCD}} + C(\beta) = 9.917(3) \text{ GeV} > M_{\chi_{b1}(1P)}^{\text{exp}} = 9.89278(26)(31) \text{ GeV}$$

Reconstruction Accuracy: S-wave



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

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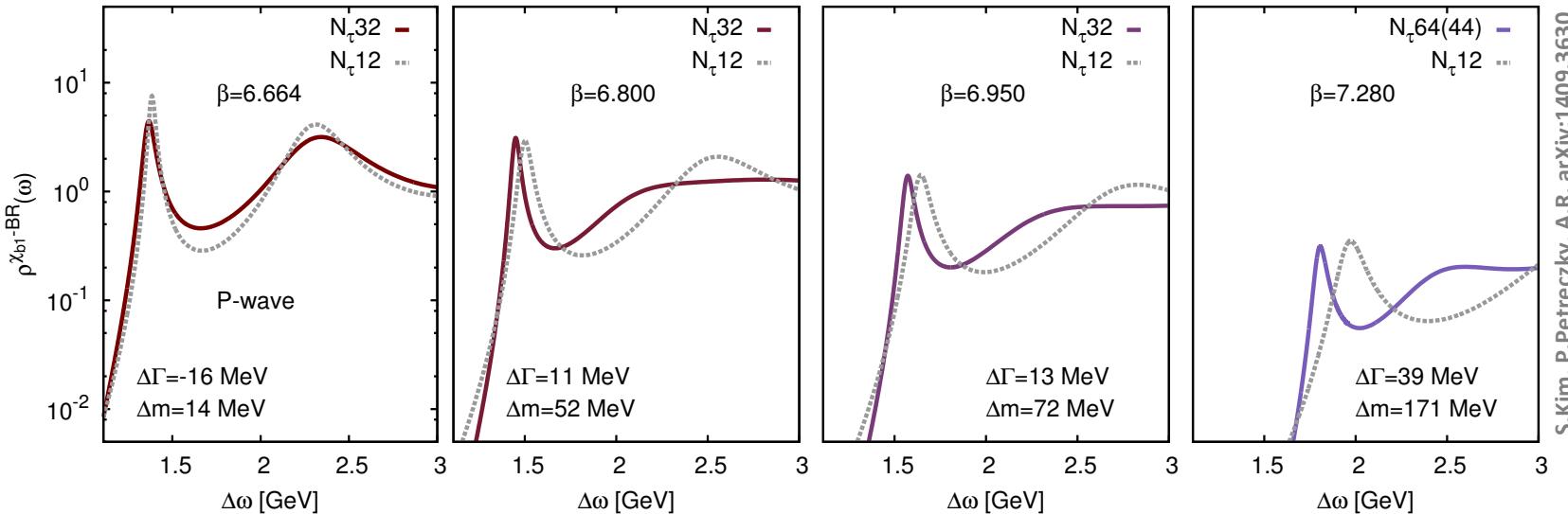


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Overall Limits: $\beta = 6.664 : \Delta m_T < 2 \text{ MeV}, \Delta \Gamma_T < 5 \text{ MeV}$
 $\beta = 7.280 : \Delta m_T < 40 \text{ MeV}, \Delta \Gamma_T < 21 \text{ MeV}$



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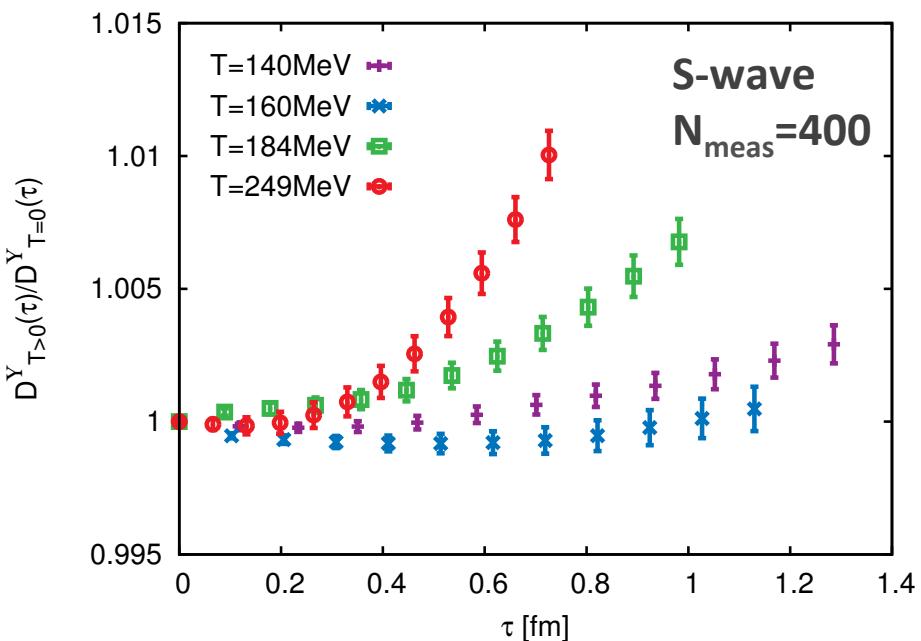


- Estimate systematics: truncate T=0 dataset ($N\tau=32/64$) to $N\tau=12$
- Due to a worse signal-to noise ratio, effect in P-wave is larger than for S-wave

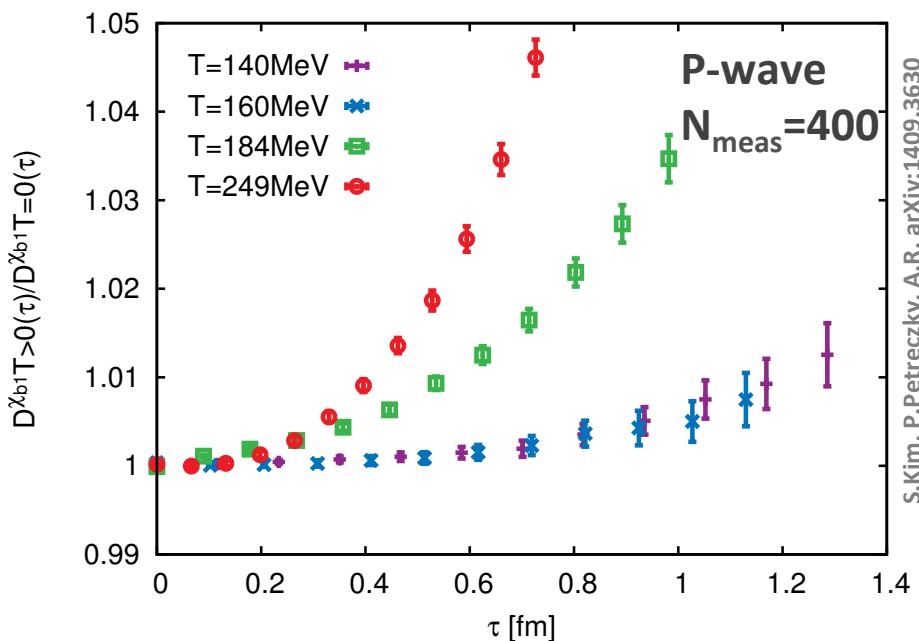
Overall Limits:

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

Bottomonium Correlators At Finite T



S-wave at most 1% change

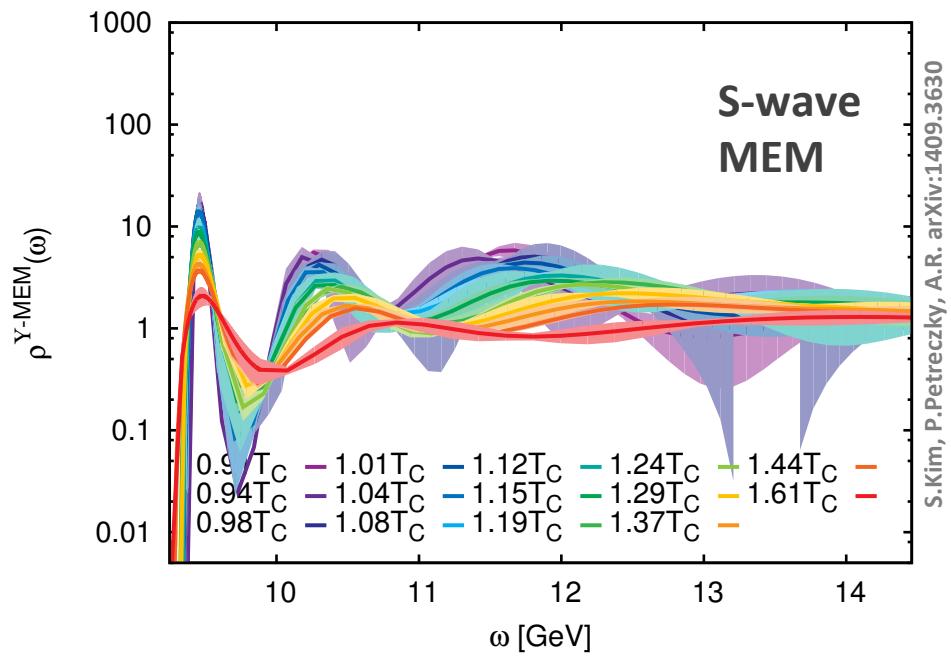
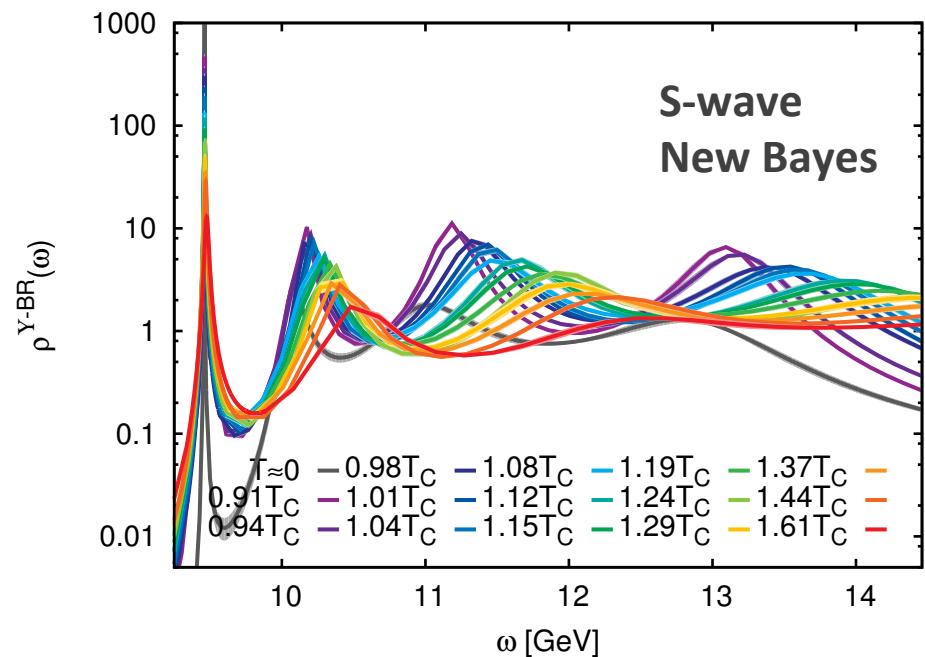


P-wave at most 5% change

- Statistically significant in-medium modification above $T=160\text{MeV}$
- Side remark: similar qualitative and quantitative behavior for η_b and h_b (scalar)



S-wave Spectral Functions At T>0

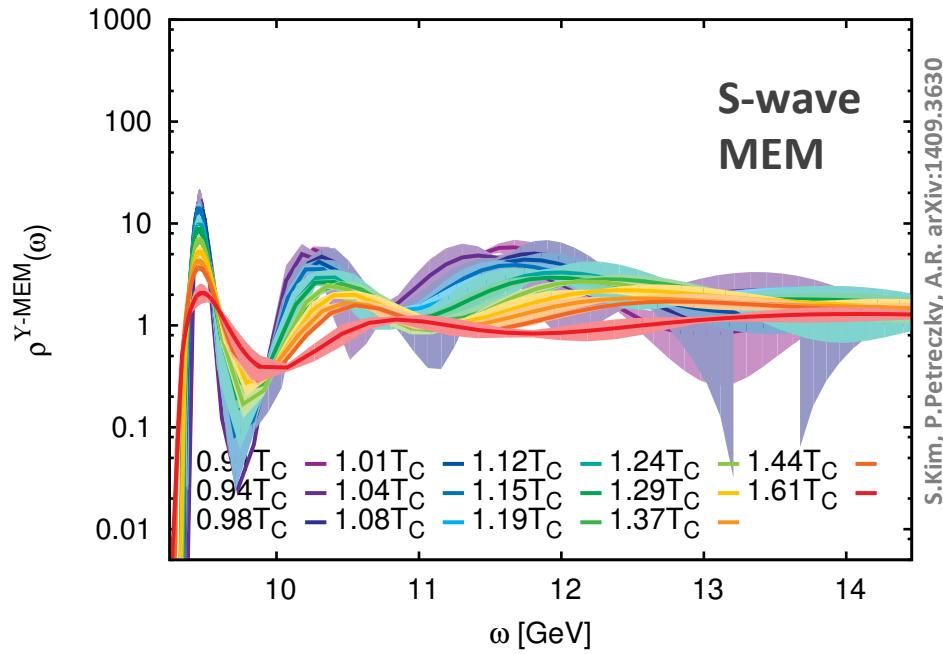
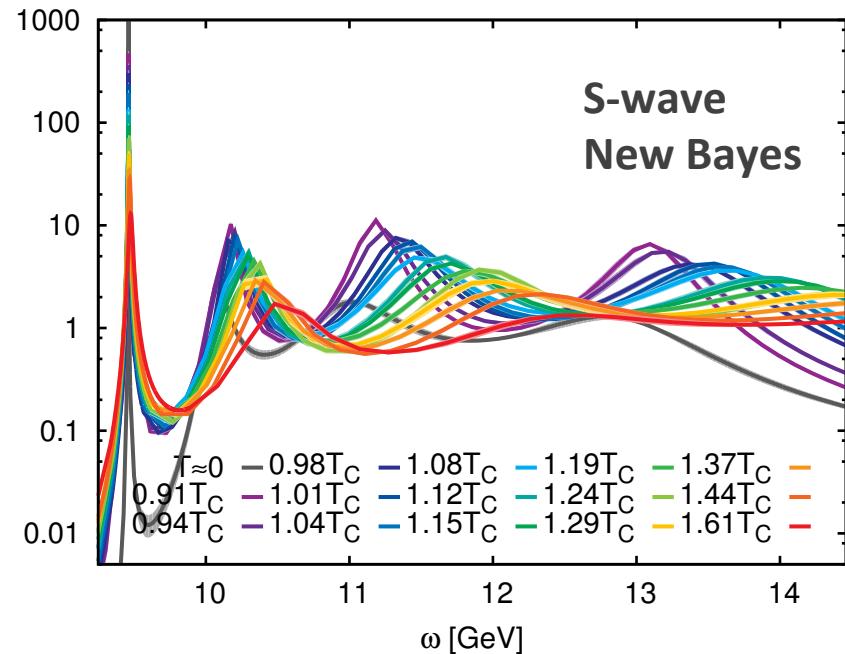


■ Bayesian reconstruction:

$N_\omega = 1200$ $I_\omega = [-1, 25]$ $\beta^{\text{num}} = 20$ $N_{\text{jack}} = 10$
 $m_i = \text{const}$ 512 bit precision, $\Delta \text{tol} = 10^{-60}$



S-wave Spectral Functions At T>0



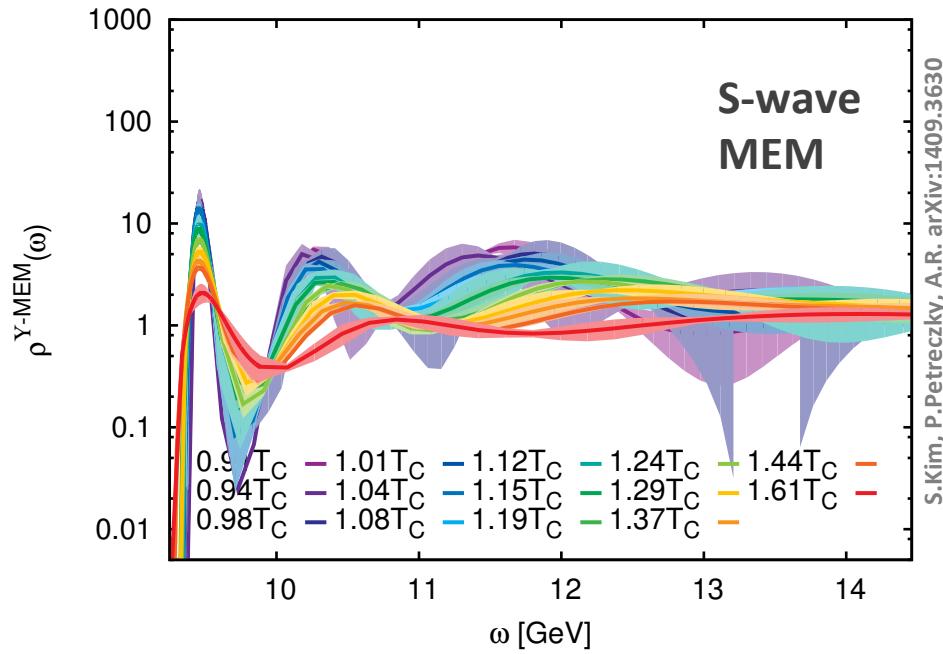
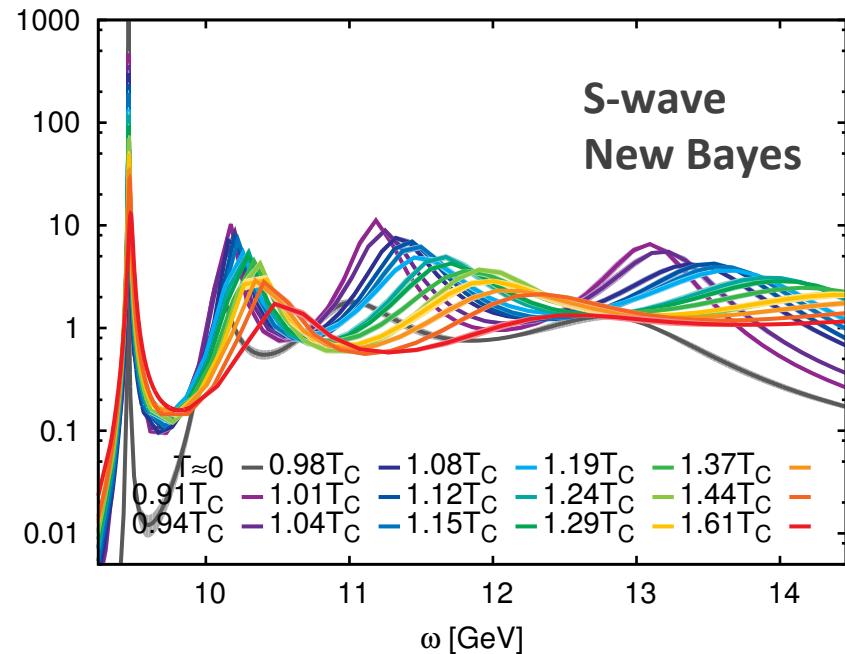
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- New Bayesian method resolves peaks much better than MEM
 - observed broadening and peak shifts at finite T smaller than accuracy limits

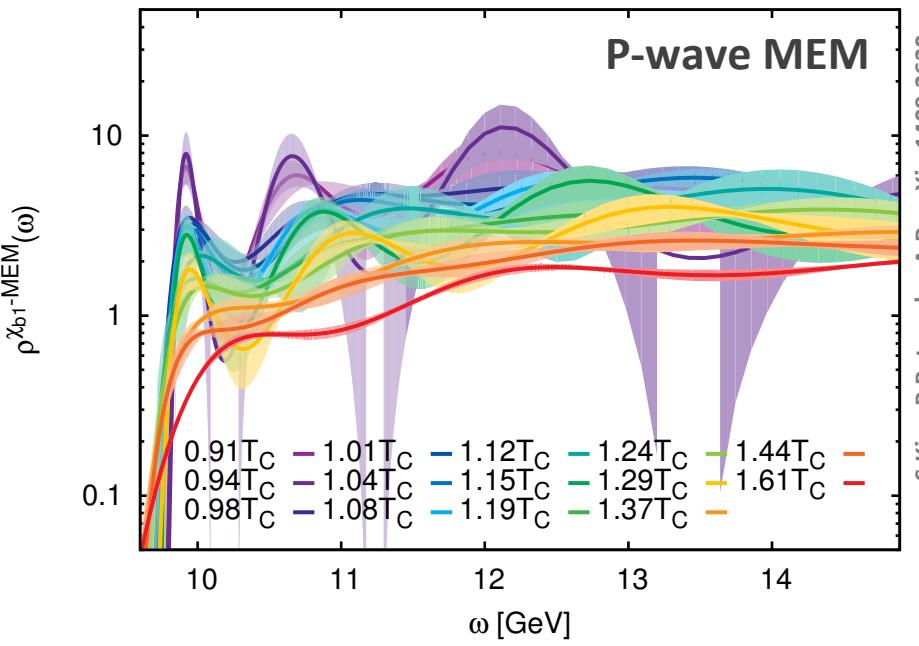
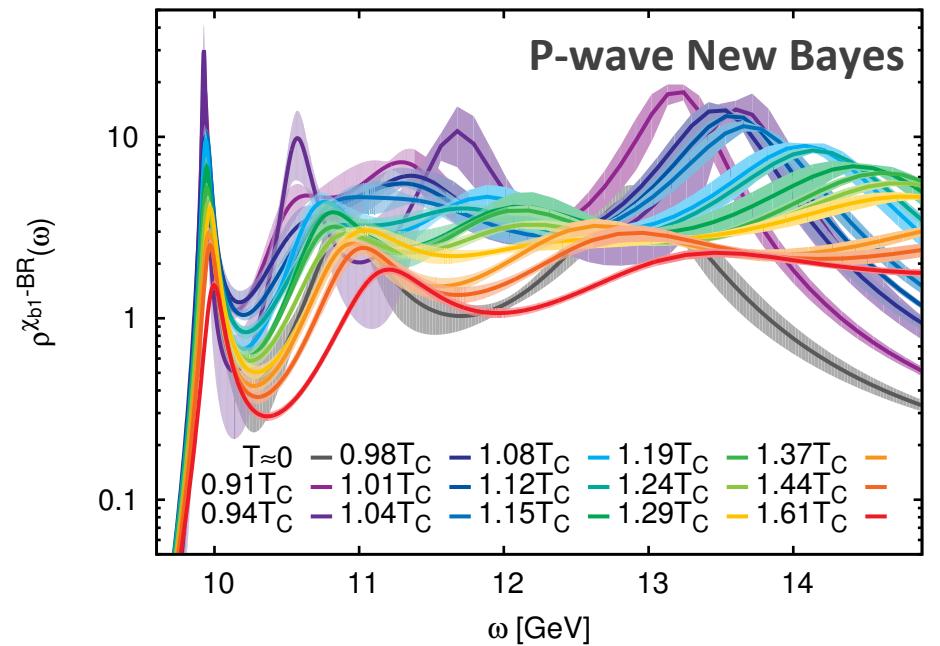
S-wave Spectral Functions At T>0



S.Kim, P.Petreczky, A.R. arXiv:1409.3630

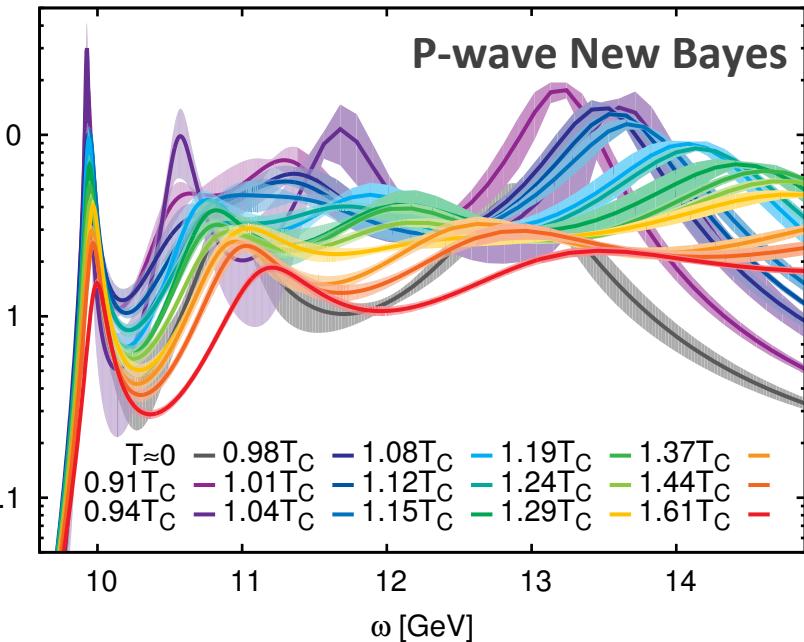
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- New Bayesian method resolves peaks much better than MEM
 - observed broadening and peak shifts at finite T smaller than accuracy limits
- Well defined **ground state peak present up to $1.61T_c = 249$ MeV**

P-wave Spectral Functions At T>0

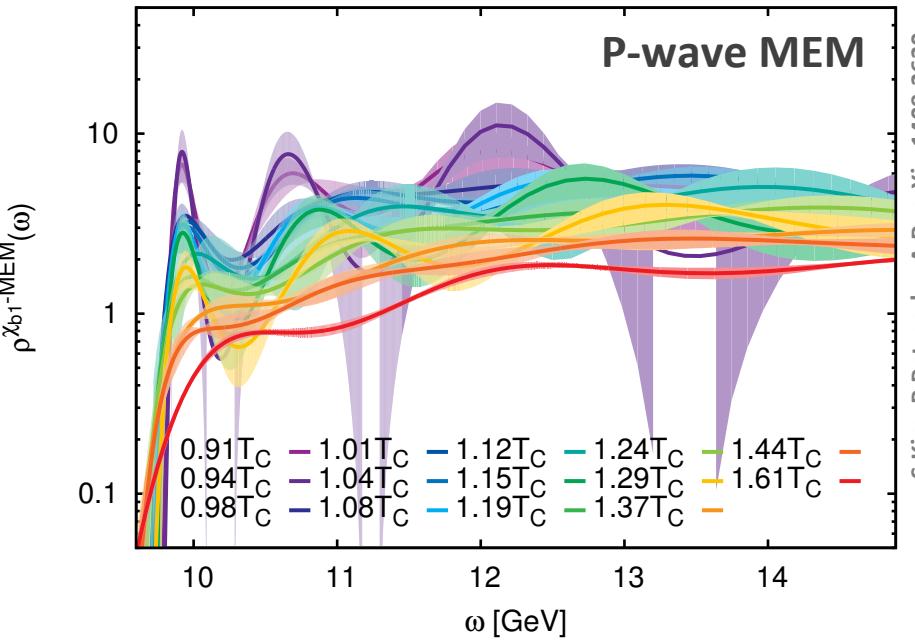


- Worse signal to noise ratio leads to larger Jackknife errors than for S-wave
- observed broadening and peak shifts also smaller than accuracy limits

P-wave Spectral Functions At T>0



**Ground state peak visible
up to $T=1.61T_c$**



**Ground state peak disappears
for $T>1.29T_c$**

- Worse signal to noise ratio leads to larger Jackknife errors than for S-wave
 - observed broadening and peak shifts also smaller than accuracy limits
- New approach finds well defined peak up to highest T investigated 249 MeV

MEM result similar to FASTSUM G. Aarts et. al. JHEP 1407 (2014) 097

Systematic Assessment Of P-wave Survival



- Peaked features can arise from either physics or numerics (c.f. Gibbs ringing)

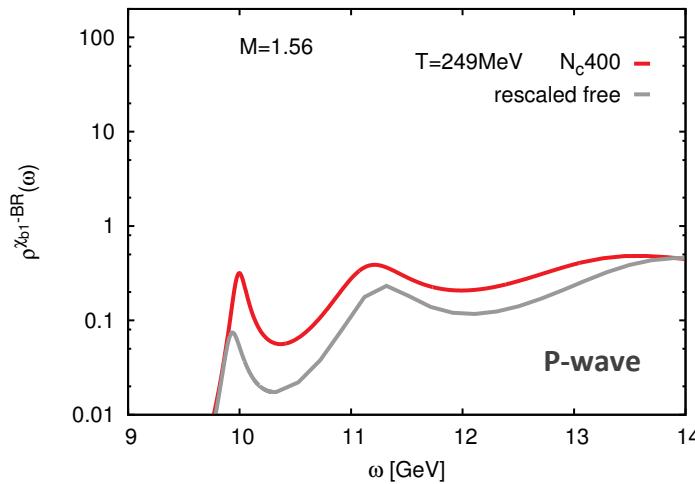
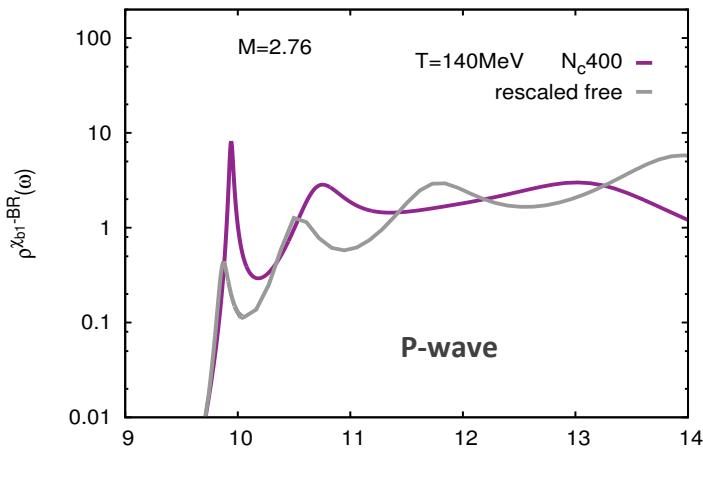
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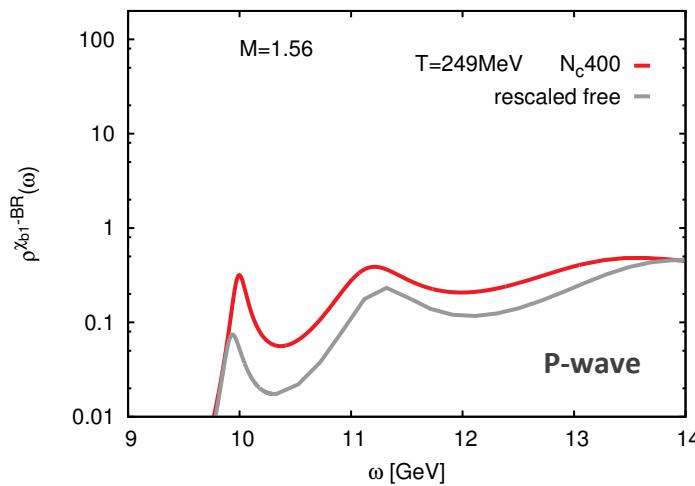
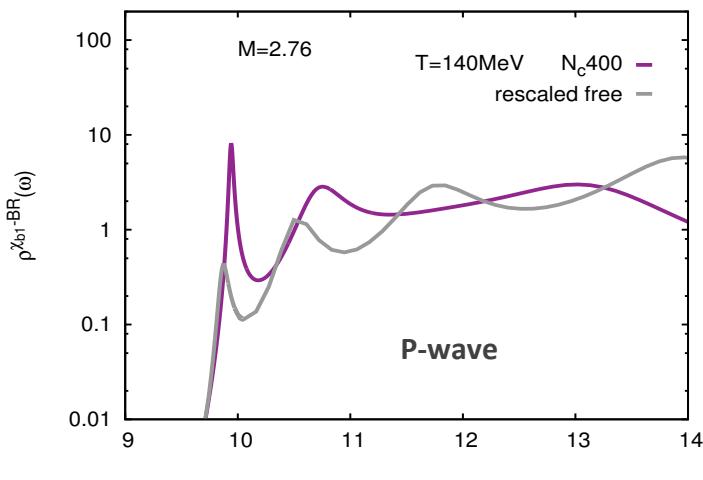
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S.Kim, P.Petreczky, A.R. arXiv:1409.3630

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S.Kim, P.Petreczky, A.R. arXiv:1409.3630

- At $T=140\text{MeV}$: clear difference between ground state peak and numerical ringing
- At $T=249 \text{ MeV}$: ground state peak less pronounced but a factor 3 remains



Conclusion

- Lattice NRQCD: efficient non-perturbative treatment of Bottomonium at T>0
- Improved Bayesian approach to spectral function reconstruction is promising
 - Improves on the MEM: higher resolution on same datasets
 - No restricted search space: accuracy suffers from loss of information alone
- On HotQCD lattices with $N_f=2+1$ light HISQ flavors ($48^3 \times 12$, $T_c=159 \pm 3$ MeV)
 - In-medium modification of correlators above $T=160$ MeV [up to 1% (Υ) and 5% (χ_{b1})]
 - S-wave and P-wave ground state spectral peak well defined up to 249 MeV
 - $N_\tau=12$ datapoints allow us to set upper bounds on in-medium modification
 - A systematic comparison between free and interacting spectra show:
S-wave and P-wave ground state survive up to at least $T=249$ MeV



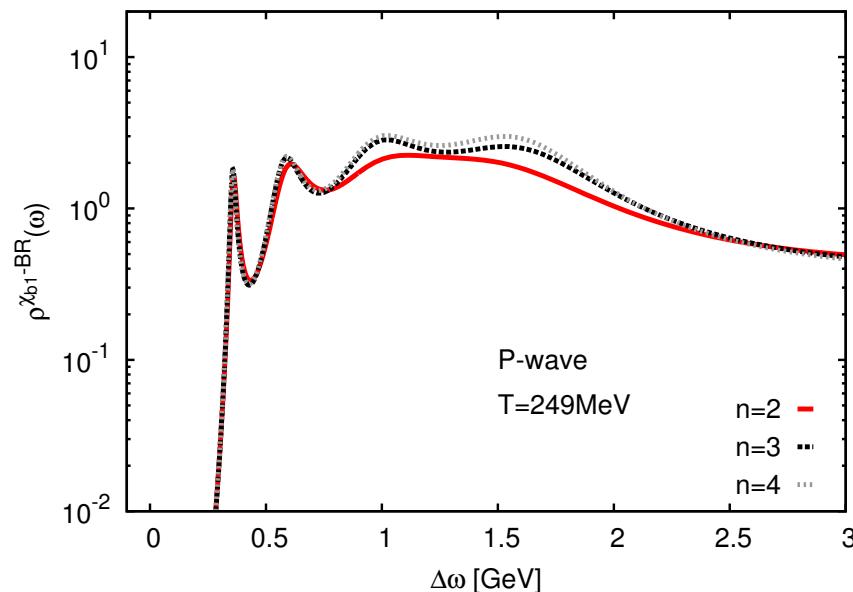
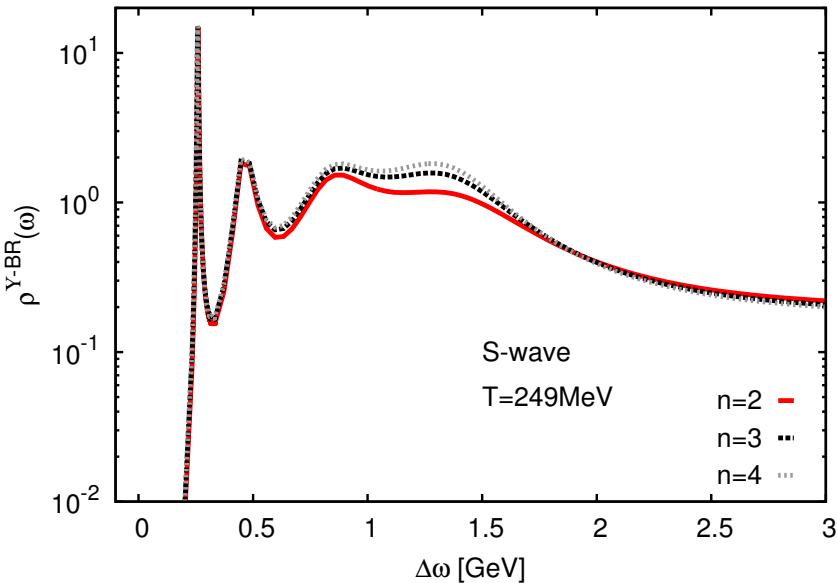
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Thank you for your attention

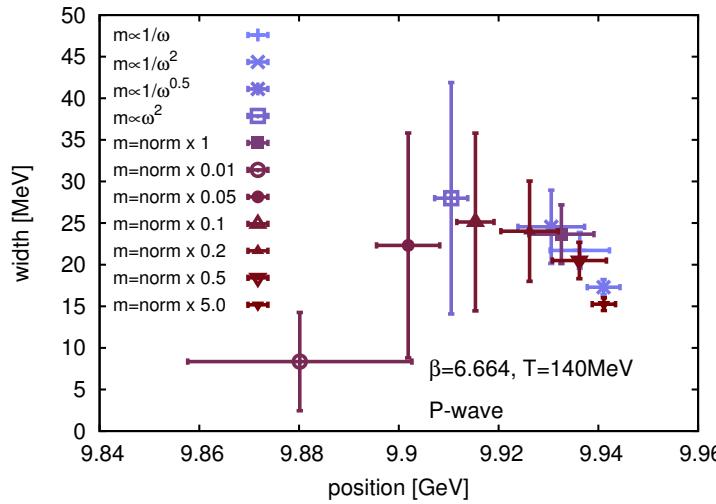
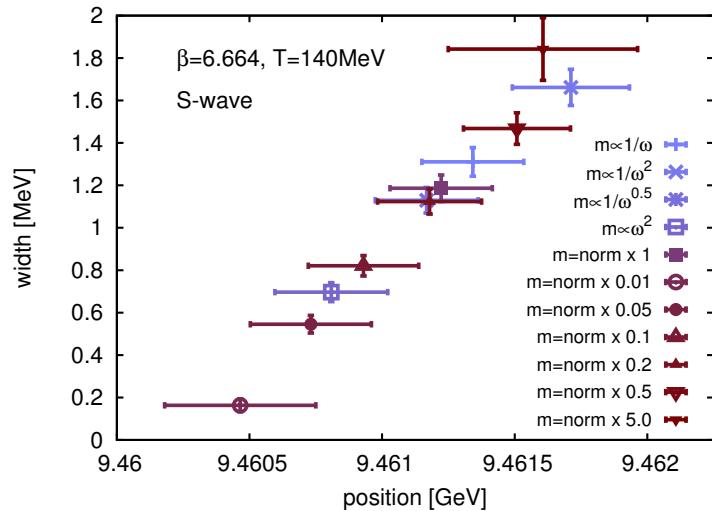
Dependence On The NRQCD Discretization

- Reduce the effective temporal step size for NRQCD propagator E.O.M.

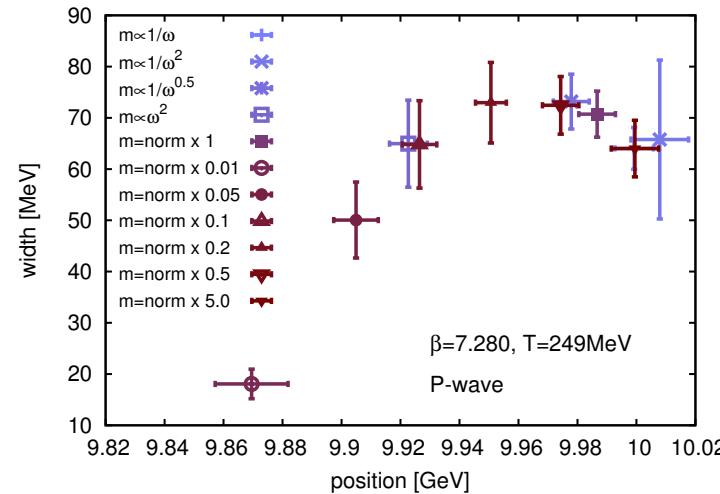
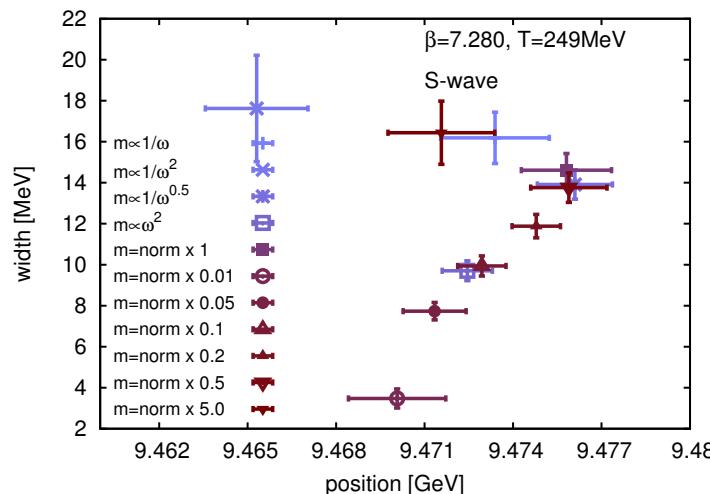
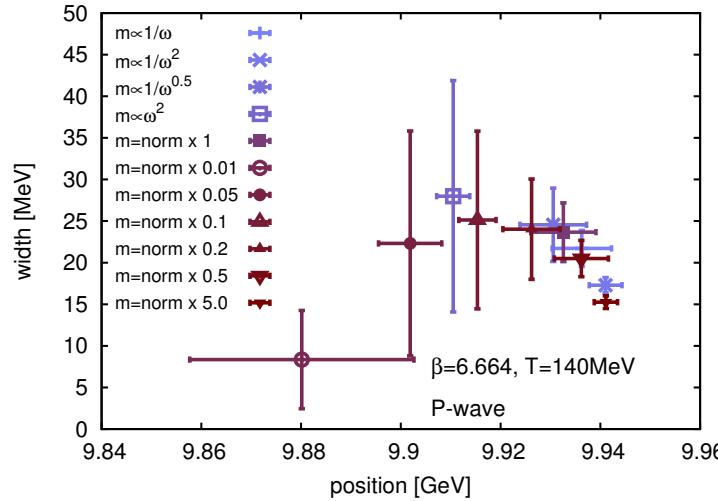
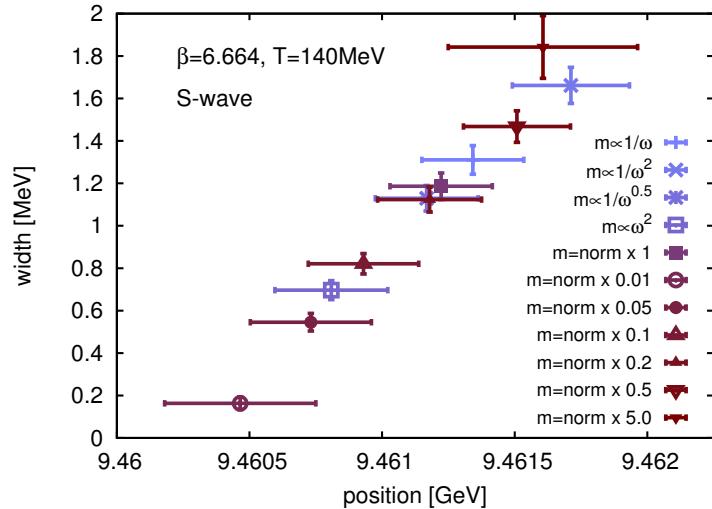


- As expected: high momentum behavior changes but IR unaffected

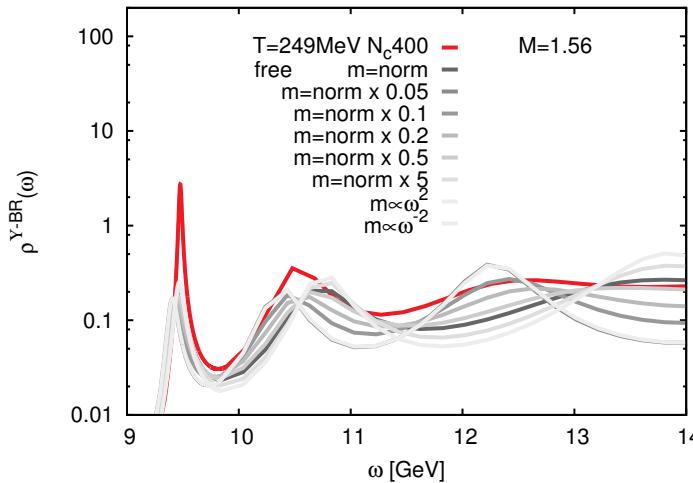
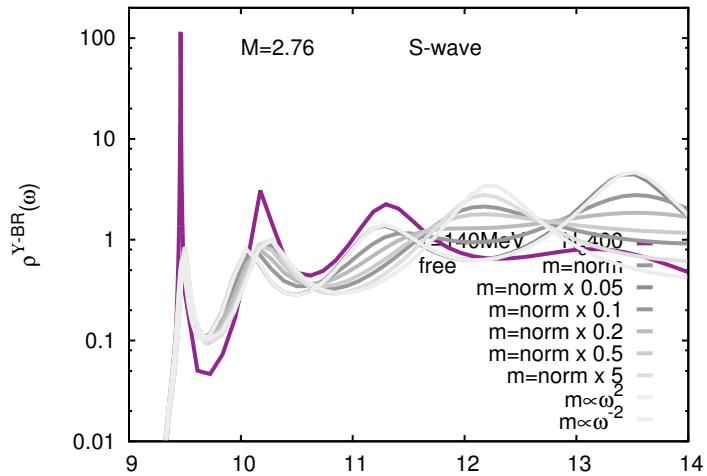
Default Model Dependence



Default Model Dependence



Free Spectra: Default Model Dependence



Free Spectra: Default Model Dependence

