# Quarkonium correlation functions at finite temperature in the charm to bottom region

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# Quarkonium in hot medium

At extremely high temperature and density

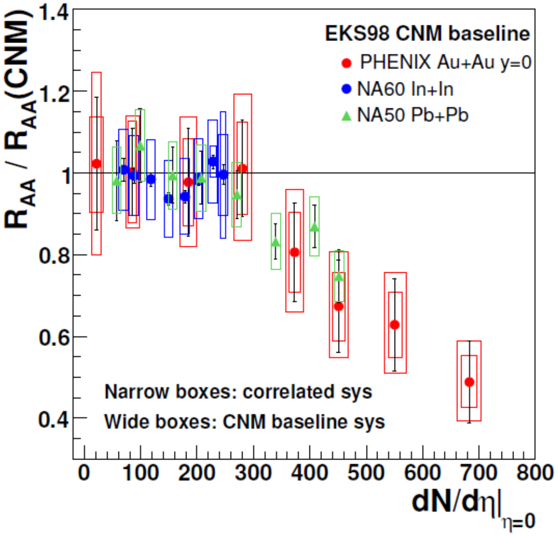
Deconfinement of quarks and gluons

**Quark Gluon Plasma (QGP)**

The Debye screening prevents heavy quark-antiquark bound state (quarkonium) formation above a certain dissociation temperature

→ important probe of QGP created in heavy ion collisions
@ RHIC, LHC

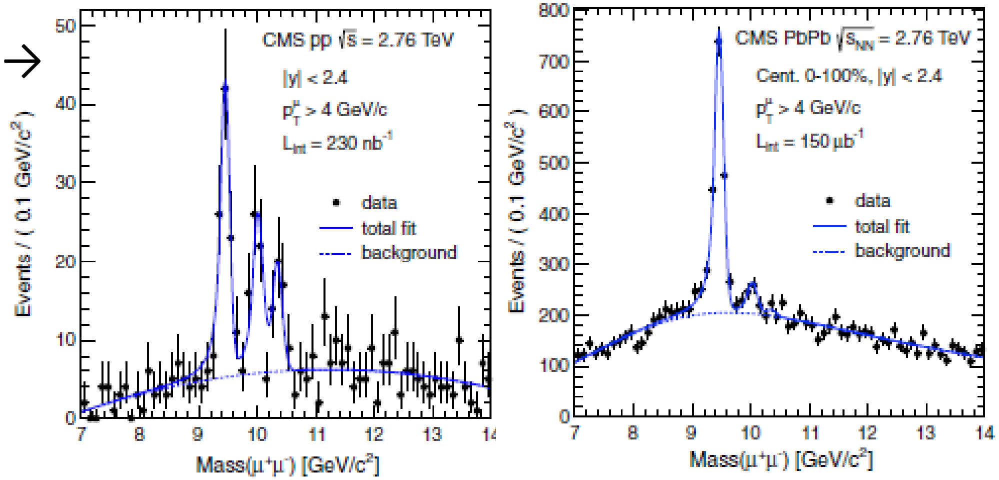
T. Matsui and H. Satz, PLB 178 (1986) 416



N. Brambilla *et al.*, EPJ C71 (2011) 1534

Sequential Bottomonium suppression @ LHC →

**Investigating dissociation temperatures of charmonia and bottomonia by first principle lattice QCD calculation is important**



S. Chatrchyan *et al.*, PRL 109 (2012) 222301

# Meson correlator & spectral function

Temporal Euclidian meson correlator

$$G_H(\tau,\vec{p}) \equiv \int d^3x e^{-i\vec{p}\cdot\vec{x}} \langle J_H(\tau,\vec{x}) J_H(0,\vec{0})\rangle$$

$$= \int_0^\infty \frac{d\omega}{2\pi} \boxed{\rho_H(\omega,\vec{p})} K(\omega,\tau)$$

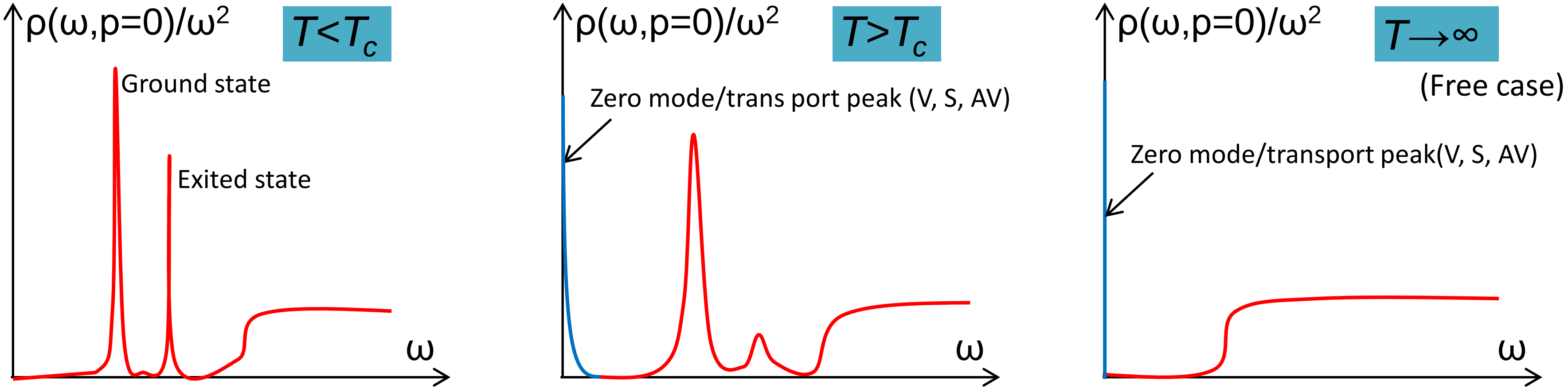
**Spectral function**

has all information about in-medium meson properties

$$J_H(\tau,\vec{x}) \equiv \bar{\psi}(\tau,\vec{x})\Gamma_H \psi(\tau,\vec{x})$$

$$K(\omega,\tau) \equiv \frac{\cosh[\omega(\tau-1/2T)]}{\sinh(\omega/2T)}$$

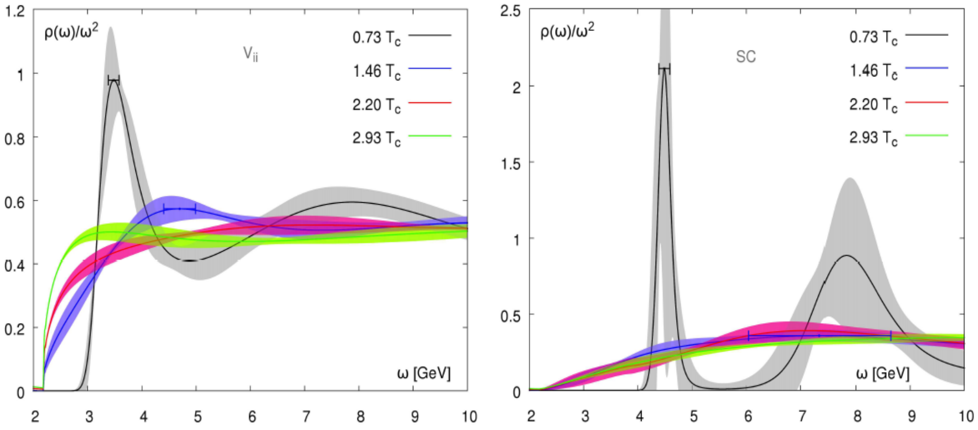
| Channel | $\Gamma_H$ | ${}^{2S+1}L_J$ | $J^{PC}$ | Quarkonia |
|---|---|---|---|---|
| Pseudoscalar (PS) | $\gamma_5$ | ${}^1S_0$ | $0^{-+}$ | $\eta_c$, $\eta_b$ |
| Vector (V) | $\gamma_i$ | ${}^3S_1$ | $1^{--}$ | $J/\psi$, $\Upsilon$ |
| Scalar (S) | $\mathbf{1}$ | ${}^1P_0$ | $0^{++}$ | $\chi_{c0}$, $\chi_{b0}$ |
| Axialvector (AV) | $\gamma_i\gamma_5$ | ${}^3P_1$ | $1^{++}$ | $\chi_{c1}$, $\chi_{b1}$ |



# Recent lattice studies

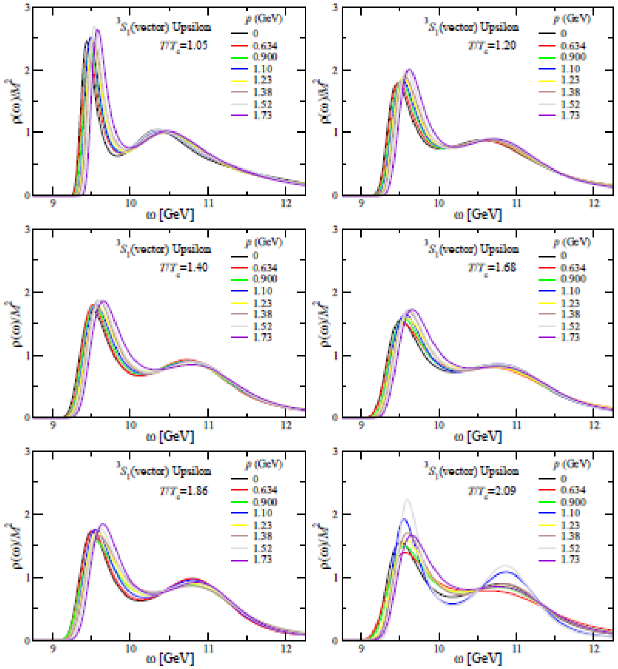
- Charmonia
  - Quenched QCD
  - Both S- and P-wave states are dissociated above ~$1.5T_c$.

H.-T. Ding *et al.*, PRD 86 (2012) 014509



- Bottomonia
  - 2-flavor, nonrelativistic QCD
  - Υ has no temperature dependence up to $2.09T_c$.
  - $\chi_{b0}$ is sensitive to the presence of thermal medium immediately above $T_c$.
  - Momentum dependence is effectively temperature independent.

G.Aarts *et al.*, PRL 106 (2011) 061602
G.Aarts *et al.*, JHEP 1303 (2012) 084



# Reconstructed correlator

$$G_{\mathrm{rec}}(\tau, T; T') \equiv \int_0^\infty d\omega \rho(\omega, T') K(\omega, \tau, T)$$

$$\frac{G(\tau, T)}{G_{\mathrm{rec}}(\tau, T; T')}$$ equals to unity at all τ

if the spectral function doesn't vary with temperature

S. Datta *et al.*, PRD 69 (2004) 094507

$$\frac{\cosh[\omega(\tau - N_\tau/2)]}{\sinh[\omega N_\tau/2]} = \sum_{\tau'=\tau;\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} \frac{\cosh[\omega(\tau' - N'_\tau/2)]}{\sinh[\omega N'_\tau/2]}$$

$$T = 1/(N_\tau a) \qquad N'_\tau = m N_\tau \qquad m = 1, 2, 3, \cdots$$

$$\boxed{G_{\mathrm{rec}}(\tau, T; T') = \sum_{\tau'=\tilde{\tau};\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} G(\tau', T')}$$

H.-T. Ding *et al.*, PRD 86 (2012) 014509

# Screening mass

Spatial meson correlator

**Screening mass**

$$G(z) \equiv \int dxdy \int_0^{1/T} d\tau \langle J_H(\tau,\vec{x}) J_H(0,\vec{0})\rangle \xrightarrow[z>>1/T]{} e^{-\boxed{M_{\rm scr}}z}$$

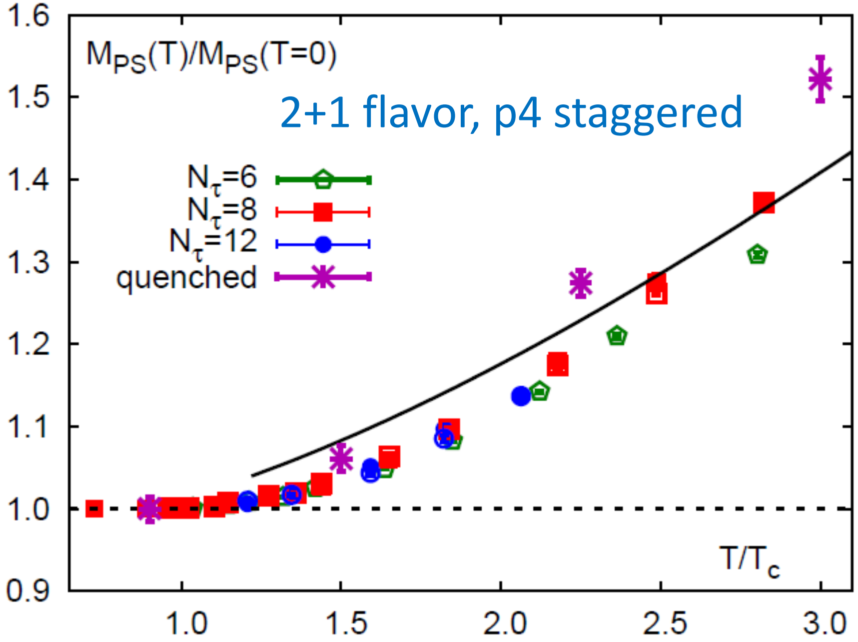
If there is a lowest lying bound state

$$\boxed{M_{\rm scr} = M}$$

High *T* limit (free case)

Quark mass

$$\boxed{M_{\rm scr} = 2\sqrt{(\pi T)^2 + m_q^2}}$$



F. Karsch *et al.*, PRD 85 (2012) 114501

2+1 flavor, HISQ → Y. Maezawa's talk on Tue. at 14:00

# Simulation setup

- Standard Wilson gauge & O(a)-improved Wilson quark actions
- In quenched QCD
- $\beta = 7.192$, $r_0 = 0.49$ fm → a = 0.0190 fm ($a^{-1} = 10.4$ GeV)
- On $96^3 \times N_\tau$ isotropic lattices

| $N_\tau$ | 48 | 32 | 28 | 24 |
|---|---|---|---|---|
| $T/T_c$ | 0.80 | 1.2 | 1.4 | 1.6 |
| $N_{\rm conf}$ | 170 | 219 | 193 | 220 |

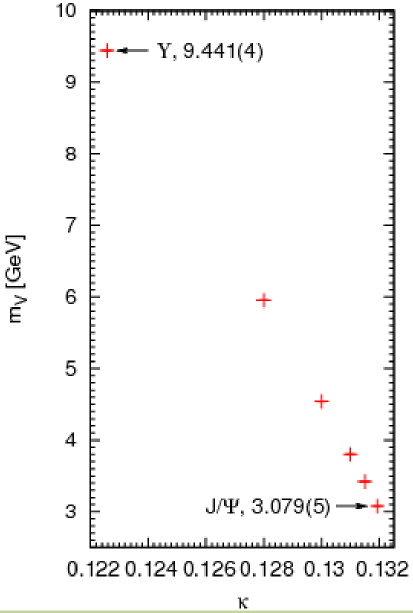
$T_c \simeq 270$ MeV

- 6 κ values corresponding to the vector meson masses in the range from J/Ψ to Υ

| $\kappa$ | 1.2557 | 1.2800 | 1.3000 | 1.3100 | 1.3150 | 1.3194 |
|---|---|---|---|---|---|---|
| $m_V$ [GeV] | 9.441(4) | 5.953(4) | 4.541(4) | 3.800(4) | 3.419(4) | 3.079(5) |

Experimental values: $m_{J/\psi}$ = 3.096.916(11) GeV, $m_\Upsilon$ = 9.46030(26) GeV

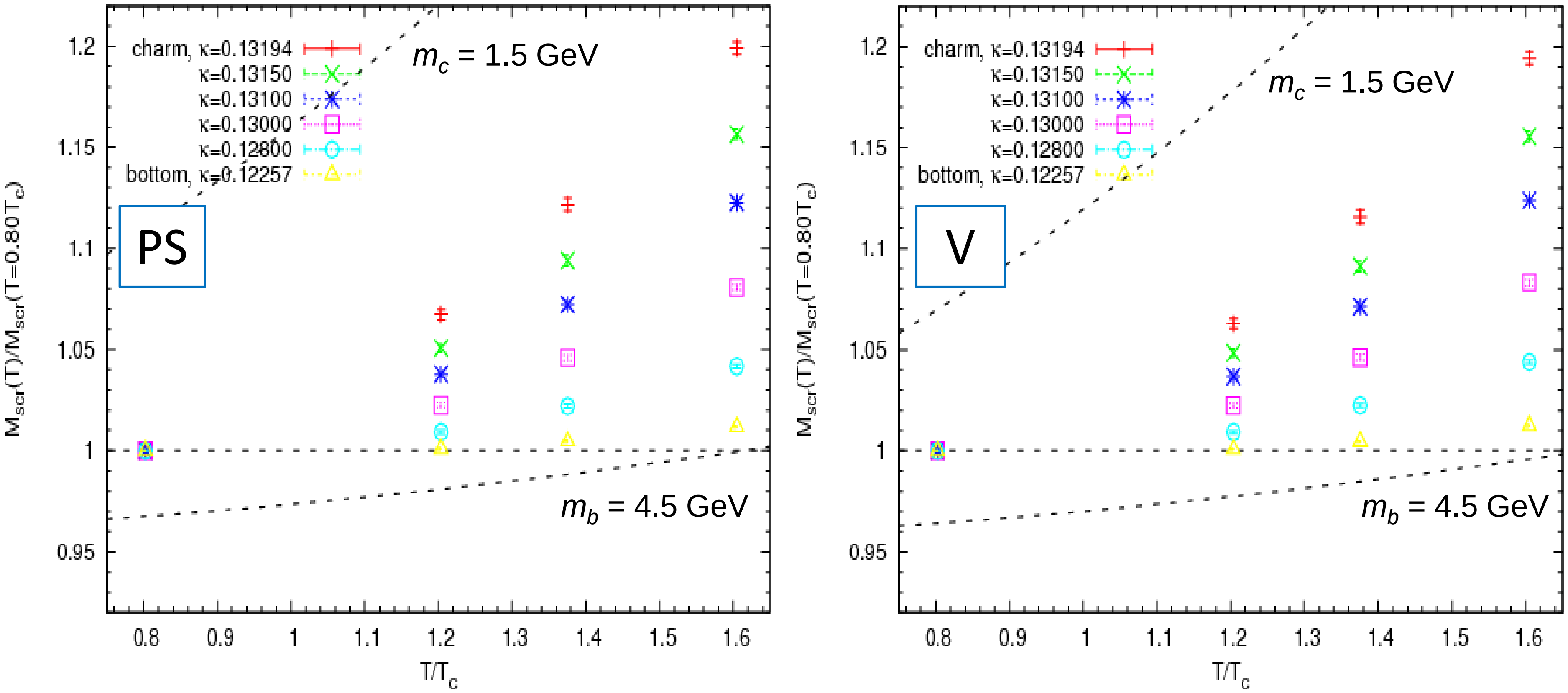
J. Beringer *et al*. [PDG], PRD 86 (2012) 010001



- Momentum: $\vec{p}a = \dfrac{2\pi\vec{k}}{N_\sigma}$ $\quad |\vec{p}| \simeq 0.7 \sim 2.0$ GeV

$$\vec{k} = (0,0,0),\ (1,0,0),\ (1,1,0),\ (2,0,0),\ (3,0,0)$$

# Screening mass: S-wave

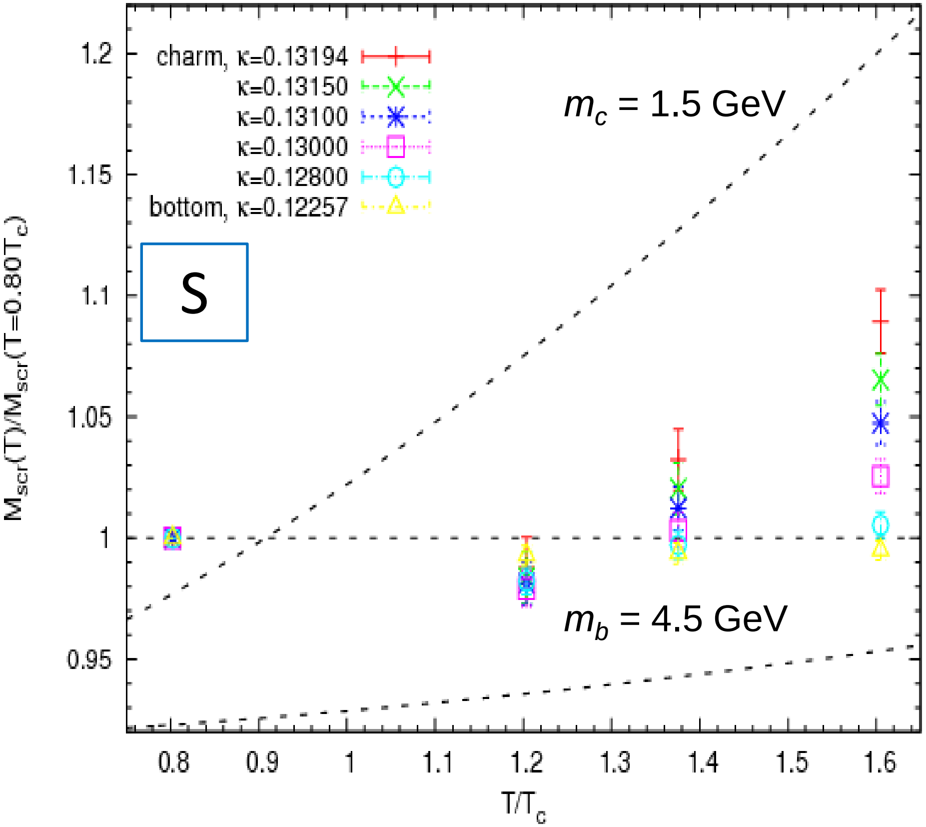


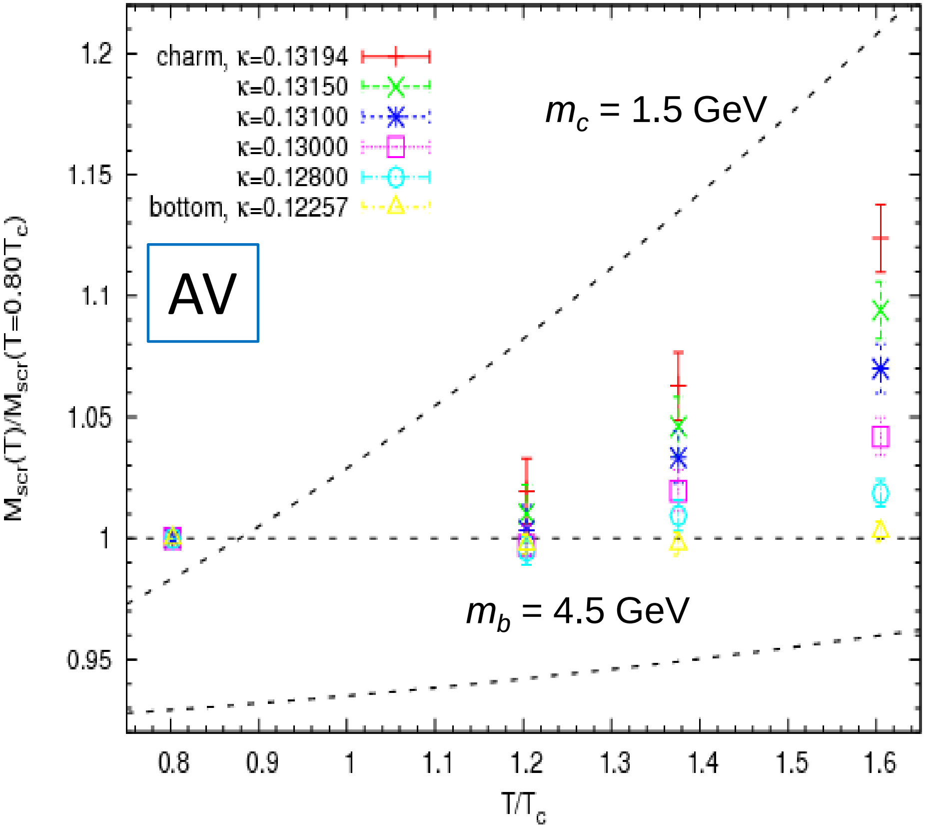
Dashed curves: $M_{\rm scr} = 2\sqrt{(\pi T)^2 + m_q^2}$

$M_{scr}$ increases monotonically as increasing temperature.

Only small temperature dependence for bottom.

# Screening mass: P-wave





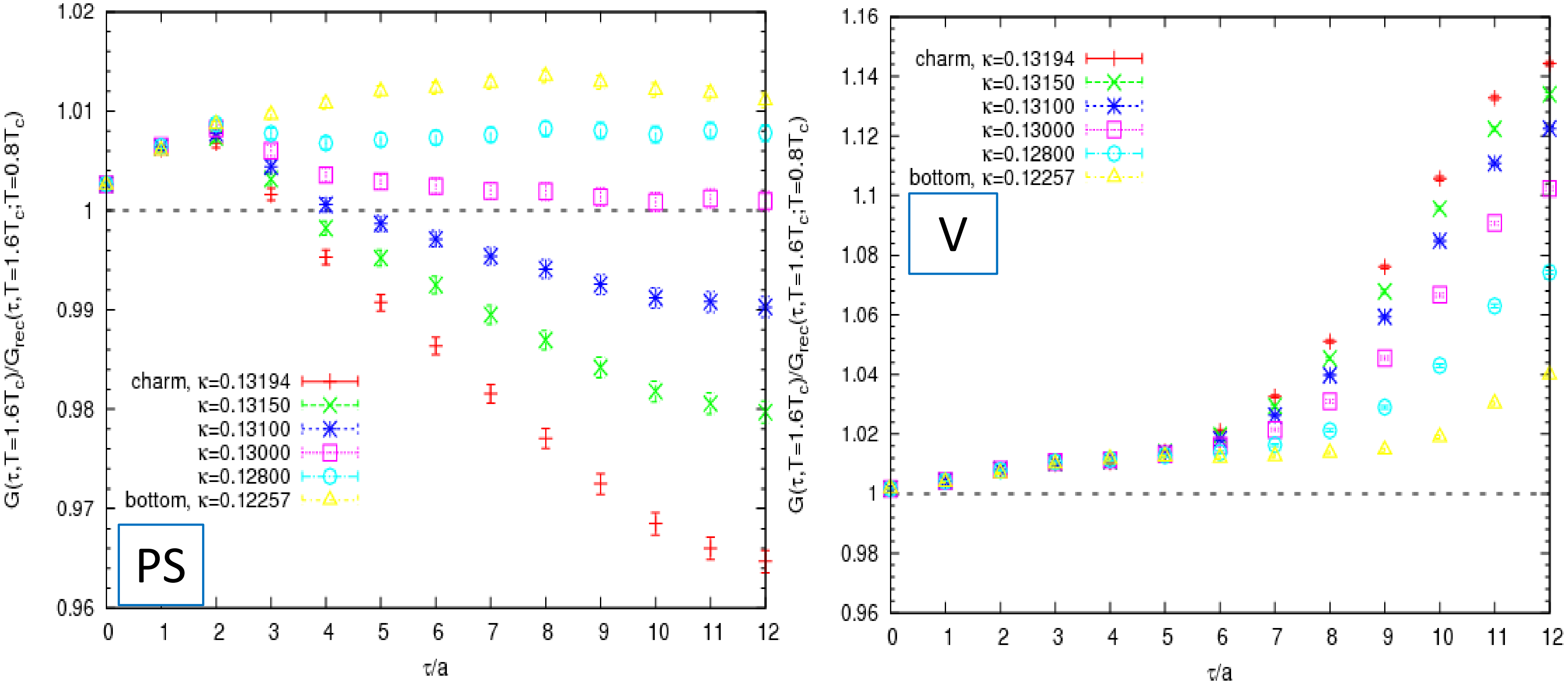
Dashed curves: $M_{\rm scr} = 2\sqrt{(\pi T)^2 + m_q^2}$

$M_{scr}$ increases as increasing temperature above $1.4T_c$.

Only small temperature dependence for bottom.

$M_{scr}$ for $\chi_{c0}$ at $1.2T_c$ is less than unity.

# Reconstructed correlator (1.6$T_c$): S-wave, p=0

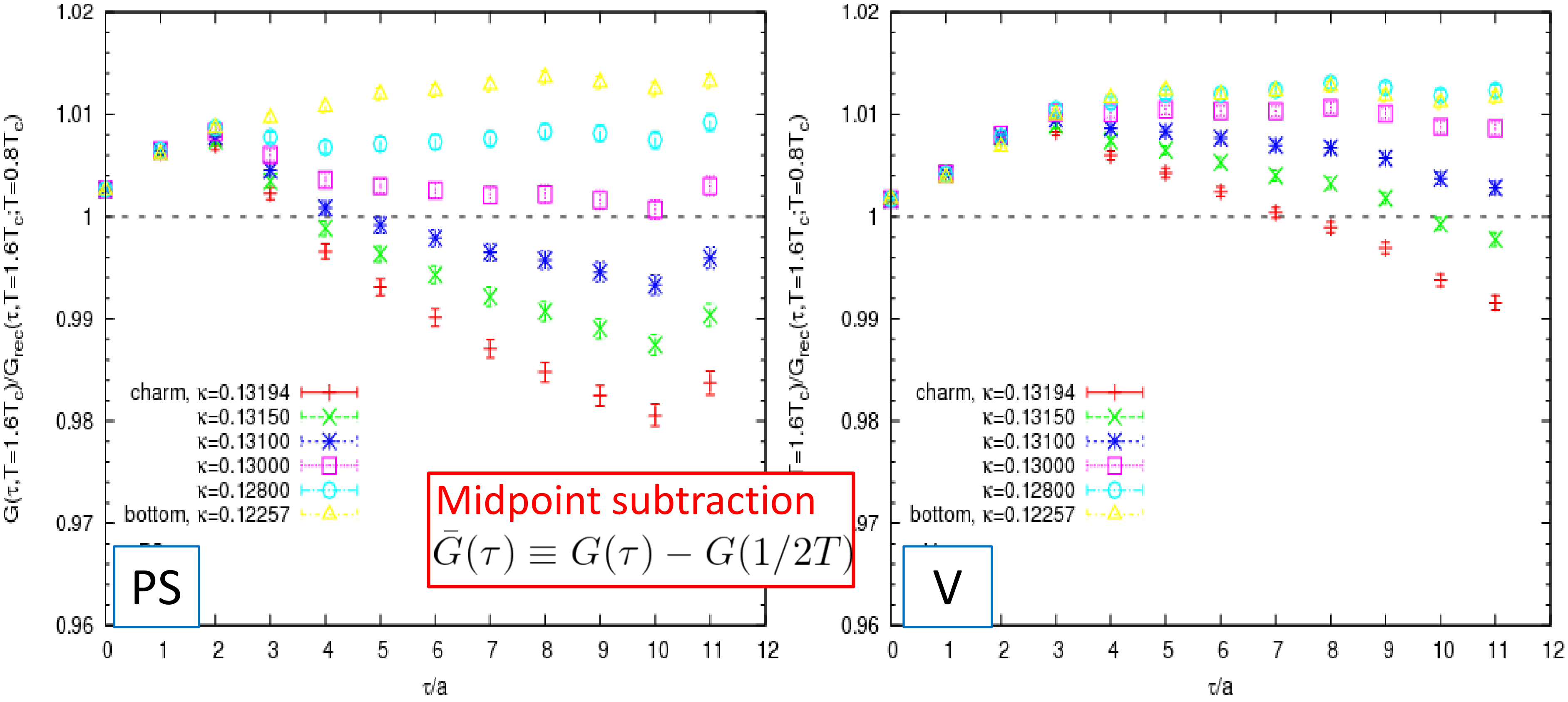


V channel is strongly enhanced at large τ/*a*.

Data for smaller quark mass has larger modification at large τ/*a*.

PS and V channels have quite different behavior from each other.

# Reconstructed correlator (1.6$T_c$): S-wave, p=0



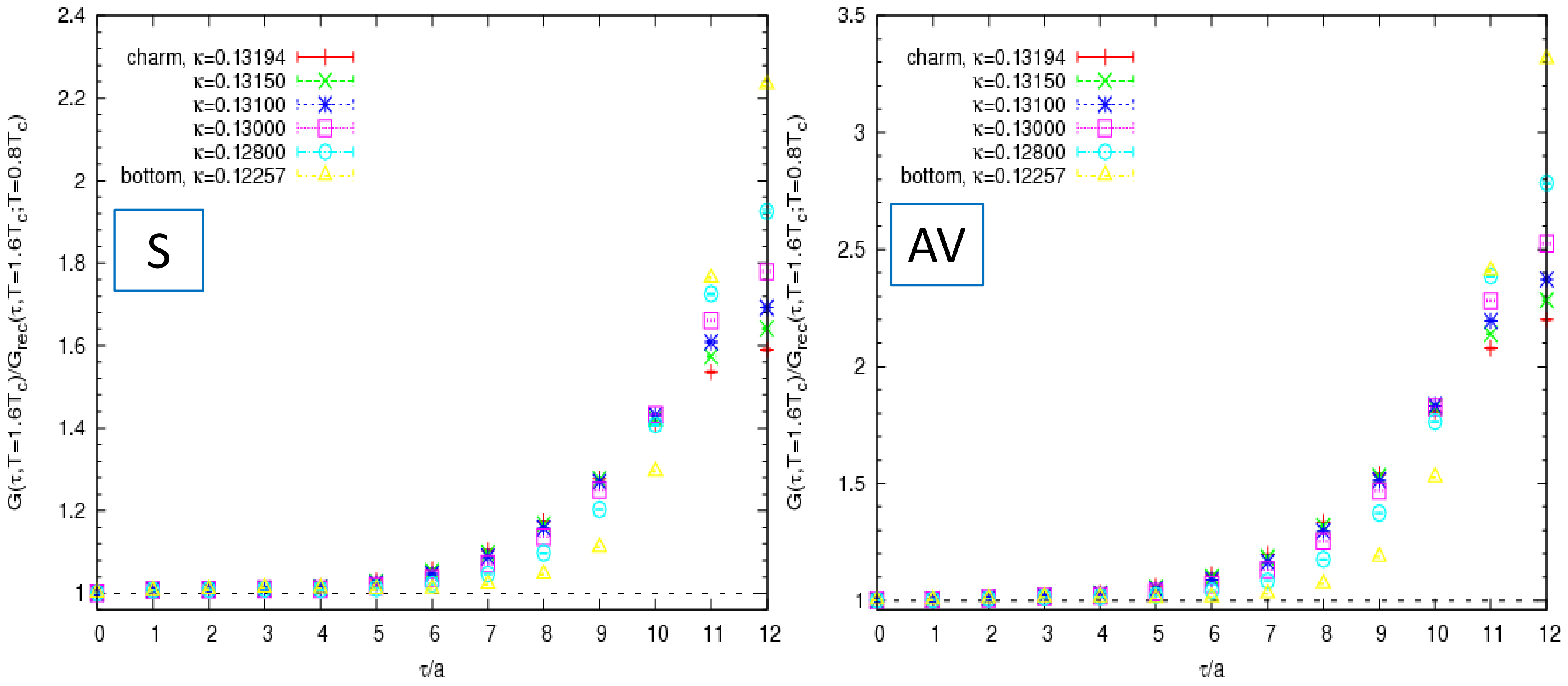
Midpoint subtraction

$$\bar{G}(\tau) \equiv G(\tau) - G(1/2T)$$

PS and V channels have similar behavior to each other in this case.

Most part of the strong enhancement at large τ/*a* for V channel comes from the zero mode contribution.

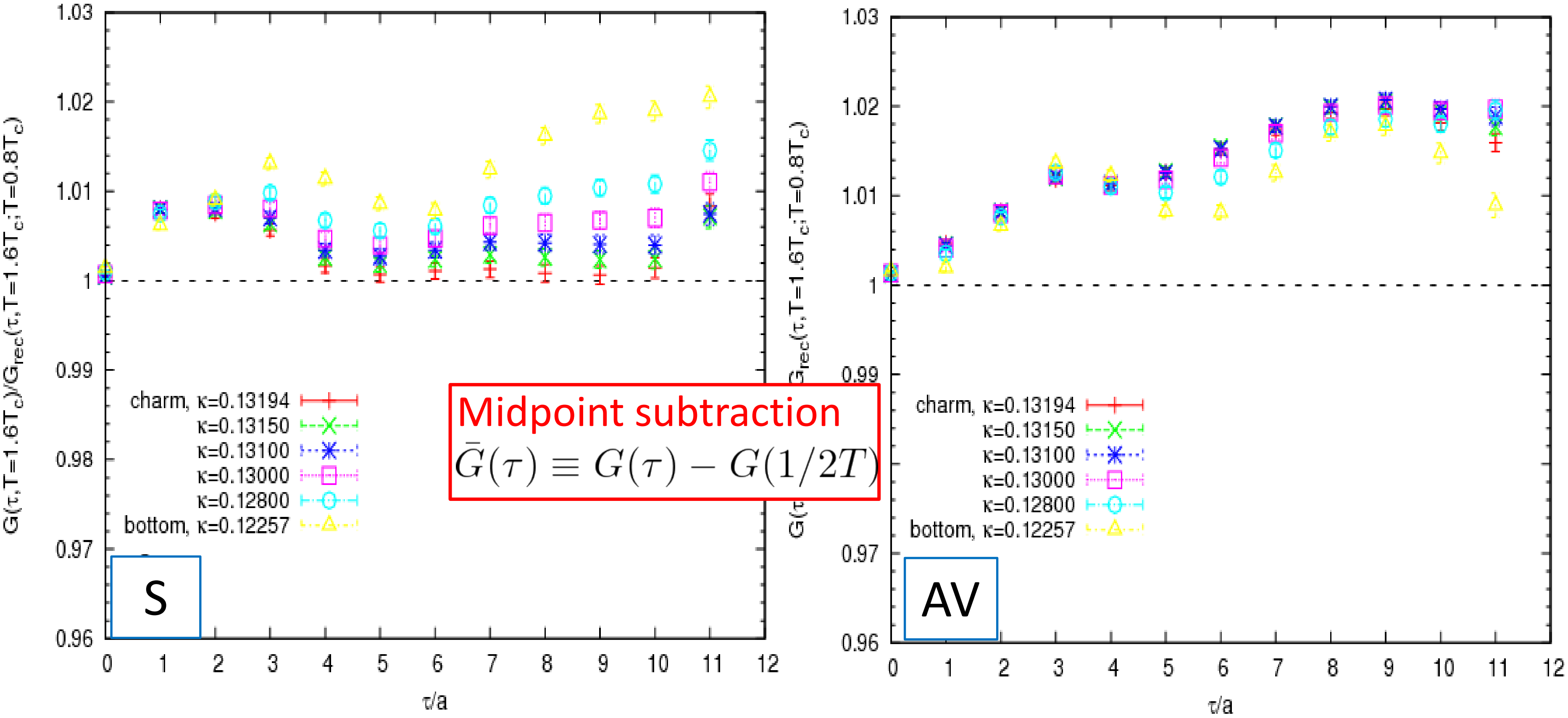
# Reconstructed correlator (1.6$T_c$): P-wave, p=0



Data at large τ/*a* is strongly enhanced.

Quark mass dependence at small τ/*a* is small, while larger quark mass data has larger modification at the largest τ/*a*.

# Reconstructed correlator (1.6$T_c$): P-wave, p=0



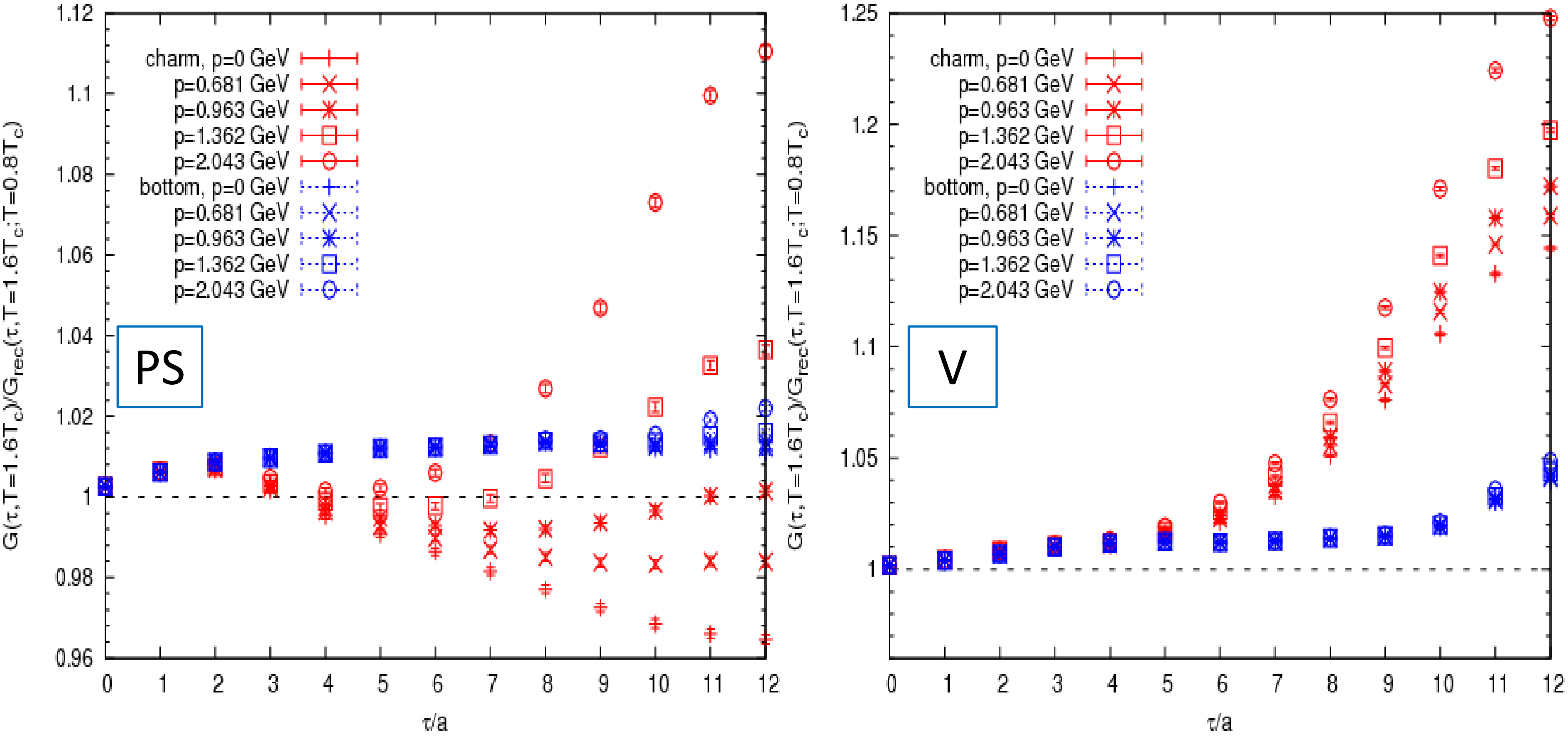
Midpoint subtraction

$$\bar{G}(\tau) \equiv G(\tau) - G(1/2T)$$

Most part of the strong enhancement at large τ/*a* comes from the zero mode contribution.

AV channel has quite small quark mass dependence.

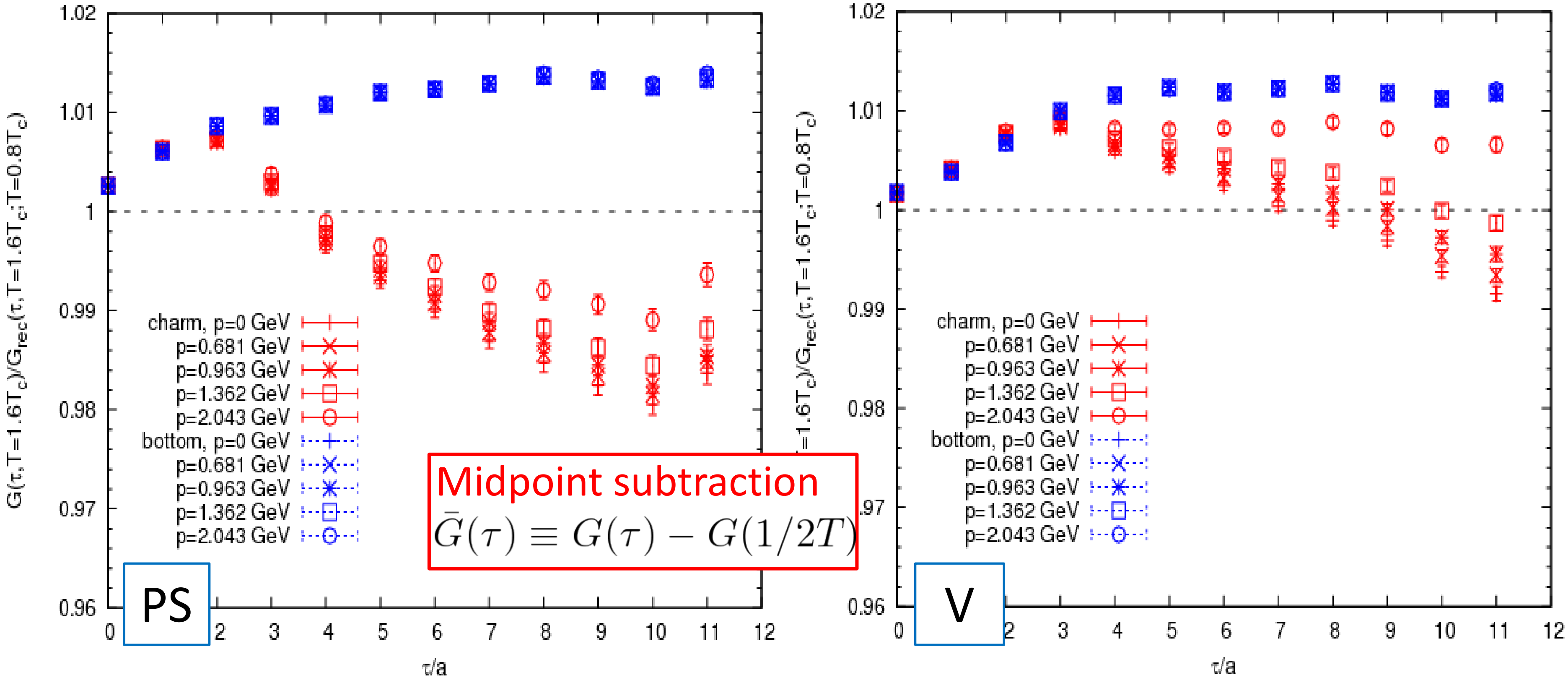
# Reconstructed correlator (1.6$T_c$): S-wave, p≠0



PS channel for charm with larger momentum is enhanced more strongly at large τ/*a*.

PS and V channels for bottom have quite small momentum dependence.

# Reconstructed correlator (1.6$T_c$): S-wave, p≠0



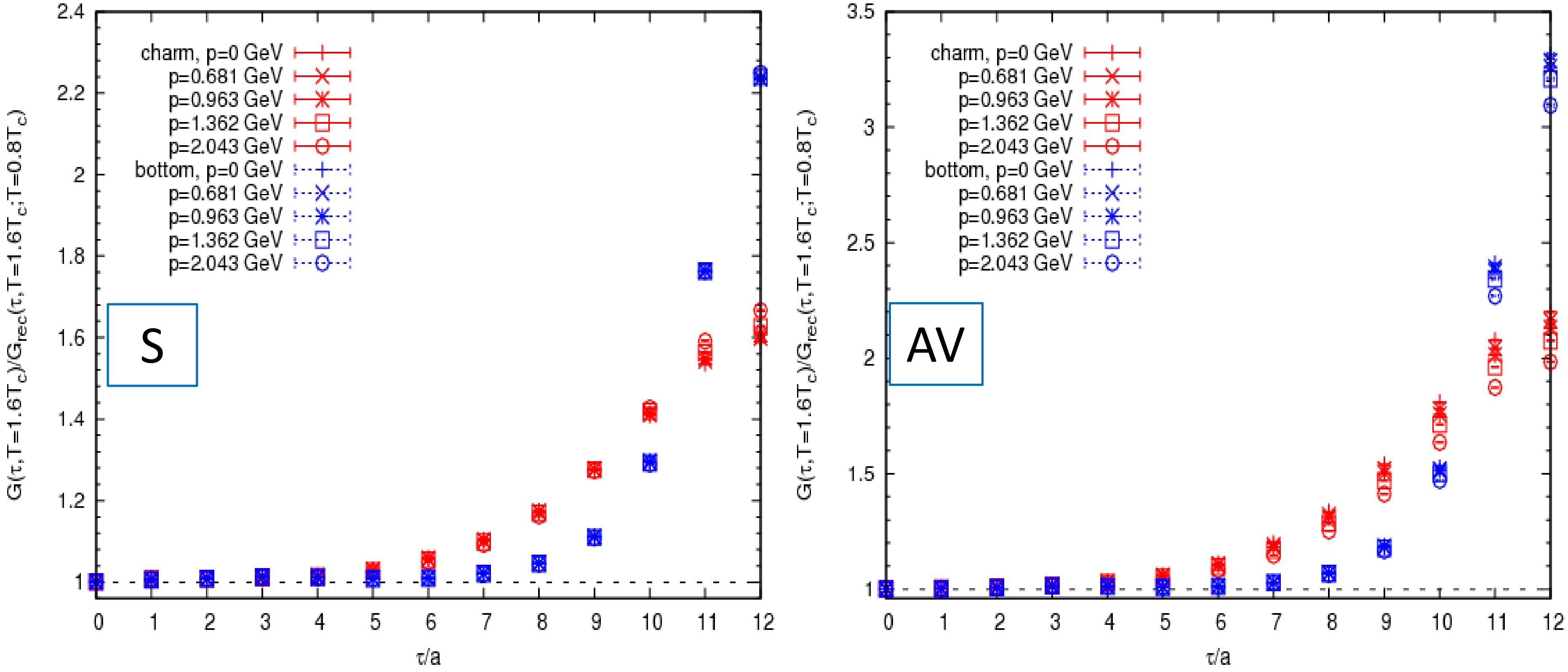
Midpoint subtraction

$$\bar{G}(\tau) \equiv G(\tau) - G(1/2T)$$

PS and V channels for charm have still small momentum dependence.

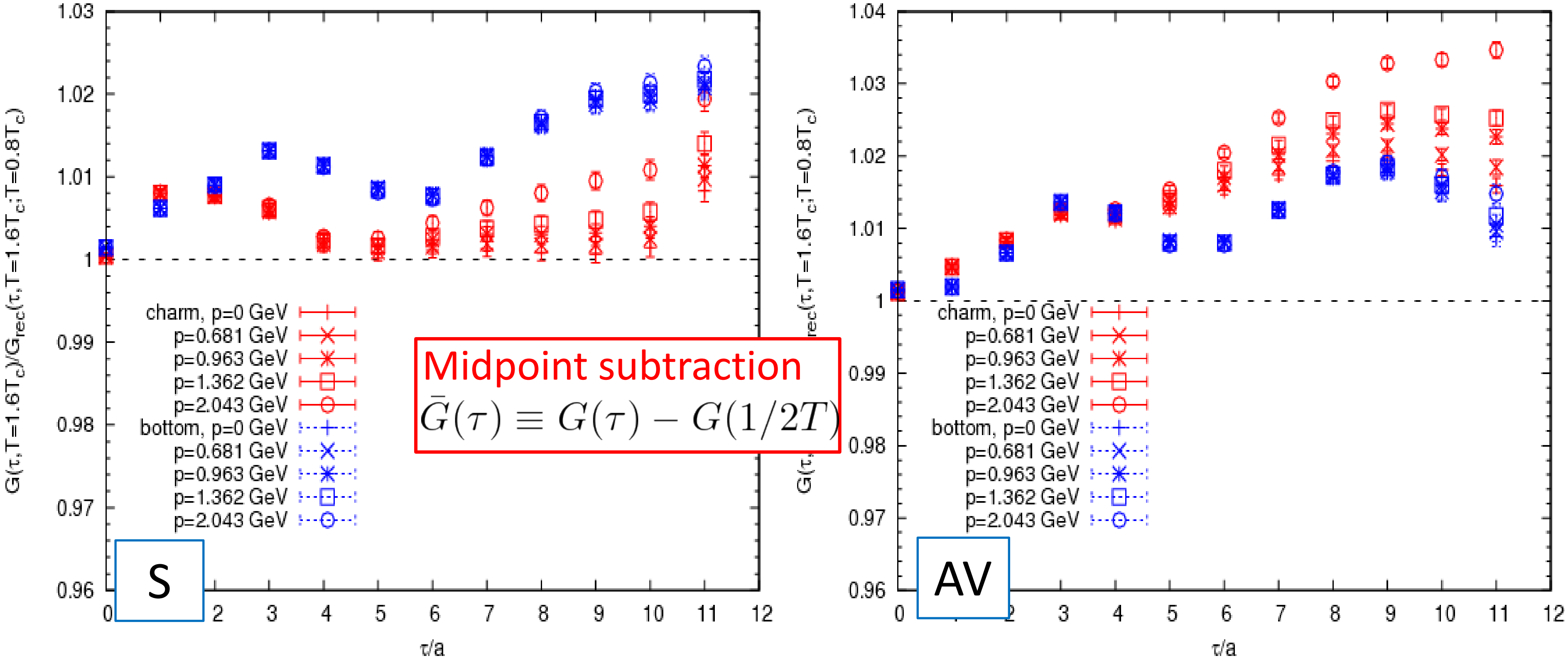
PS and V channels for bottom have no clear momentum dependence.

# Reconstructed correlator (1.6$T_c$): P-wave, p≠0



Momentum dependence is small for S channel.
Data at large τ/*a* is strongly enhanced.

# Reconstructed correlator (1.6$T_c$): P-wave, p≠0



Midpoint subtraction

$$\bar{G}(\tau) \equiv G(\tau) - G(1/2T)$$

S and AV channels for charm have small momentum dependence.

S and AV channels for bottom have quite small momentum dependence at the largest τ/*a*.

# Conclusions

- Meson correlation functions are studied
  - from $0.8T_c$ to $1.6T_c$
  - In the region of the quark mass for charmonia to bottomonia
  - at both vanishing and finite momenta
- Screening mass
  - increases as temperature increases
  - has only small temperature dependence for the bottom sector
- Temporal correlator
  - for V, S and AV channels at vanishing momentum have large zero mode contribution above $T_c$
  - for S-wave states have larger temperature effect for small quark mass at large $\tau/a$, even after the zero mode contribution is subtracted
  - PS channel for charm sector has momentum dependent zero mode contribution
  - for the charm sector has some momentum dependence
  - for the bottom sector is stable for varying momentum

# Outlook

- Finer and larger lattices
  - cutoff and volume dependences
  - continuum limit
- Estimating transport coefficients
- Investigating spectral functions directly
  - Bayesian analysis
- Investigating exited states
  - variational analysis

End