Thermal modifications of charmonia and bottomonia from spatial correlation functions

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in collaboration with

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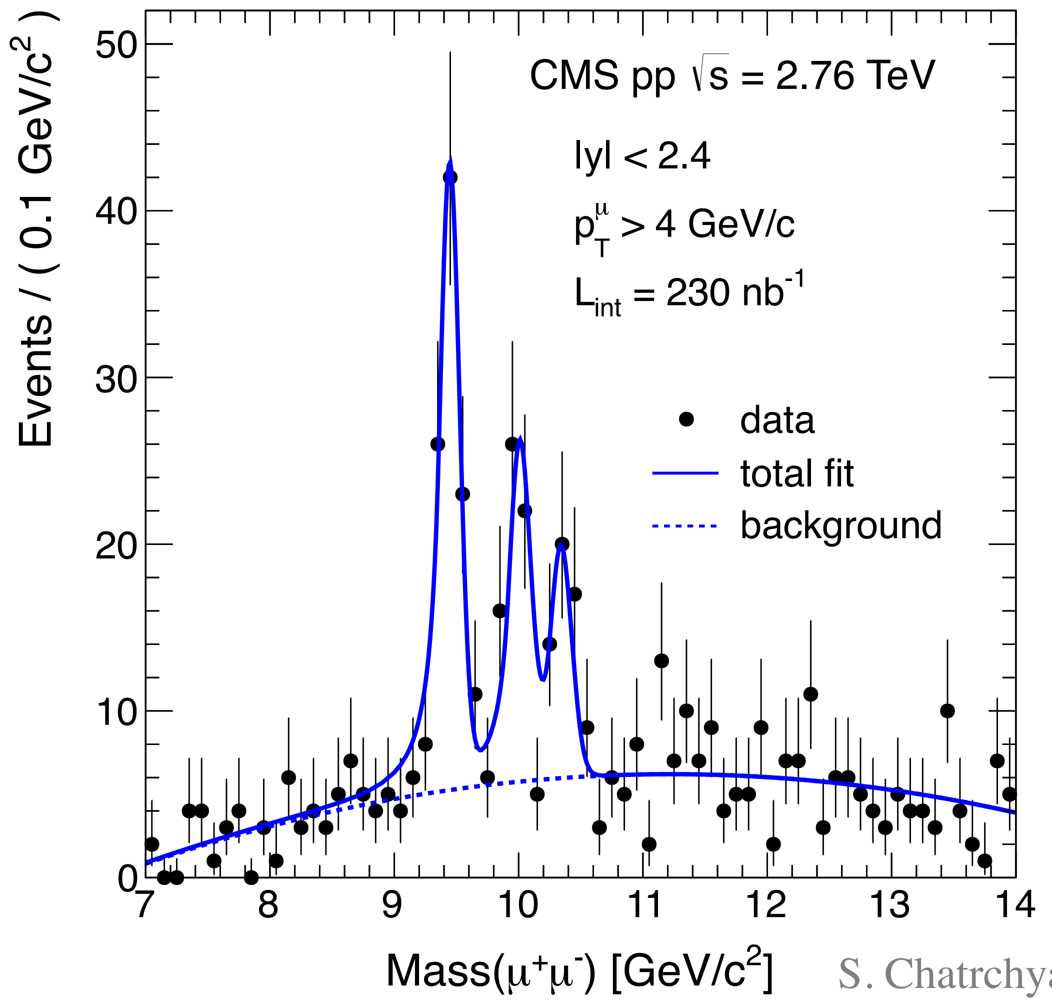
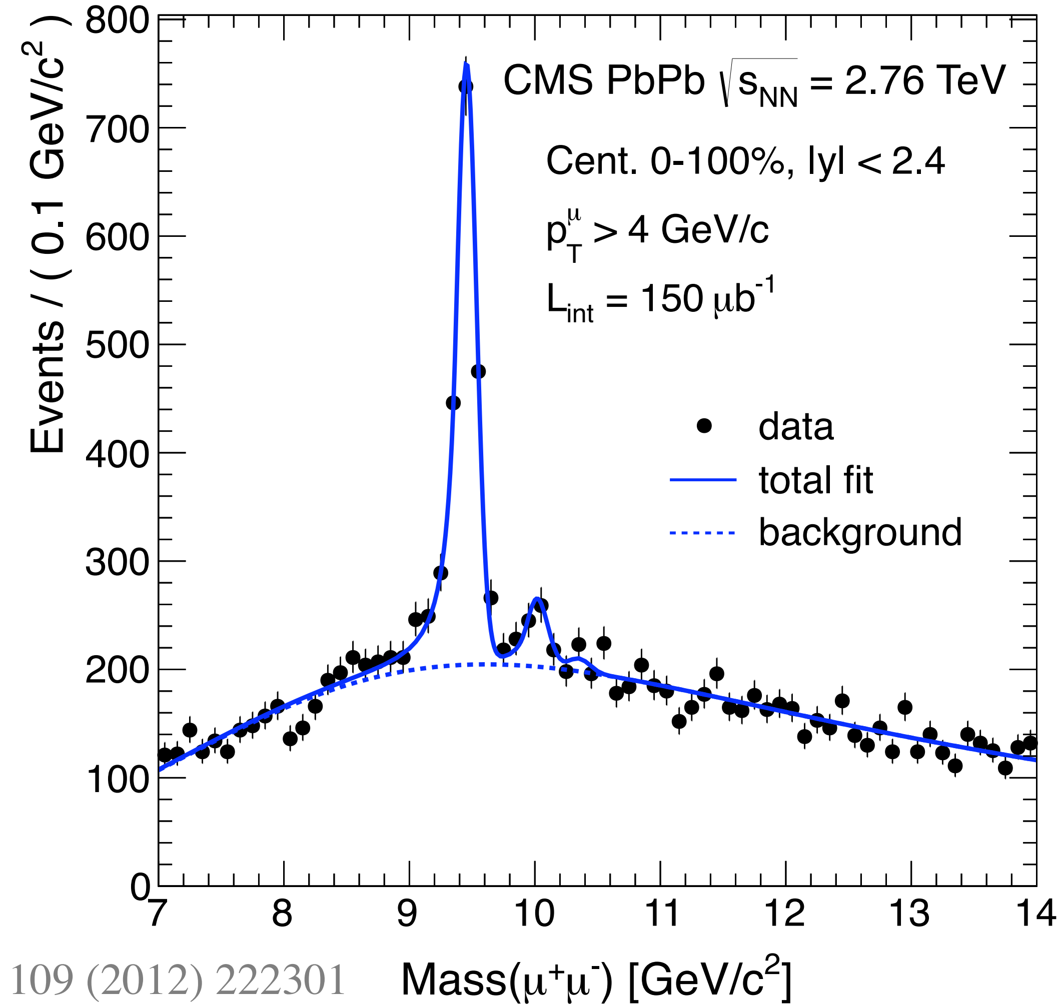
Outline

- Motivation
- Spatial Euclidean correlation functions of charmonia and bottomonia
  - Zero momentum
  - Non-zero momenta
- Screening mass of charmonia and bottomonia
  - Temperature dependence
  - Dispersion relation
- Summary

Motivation





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

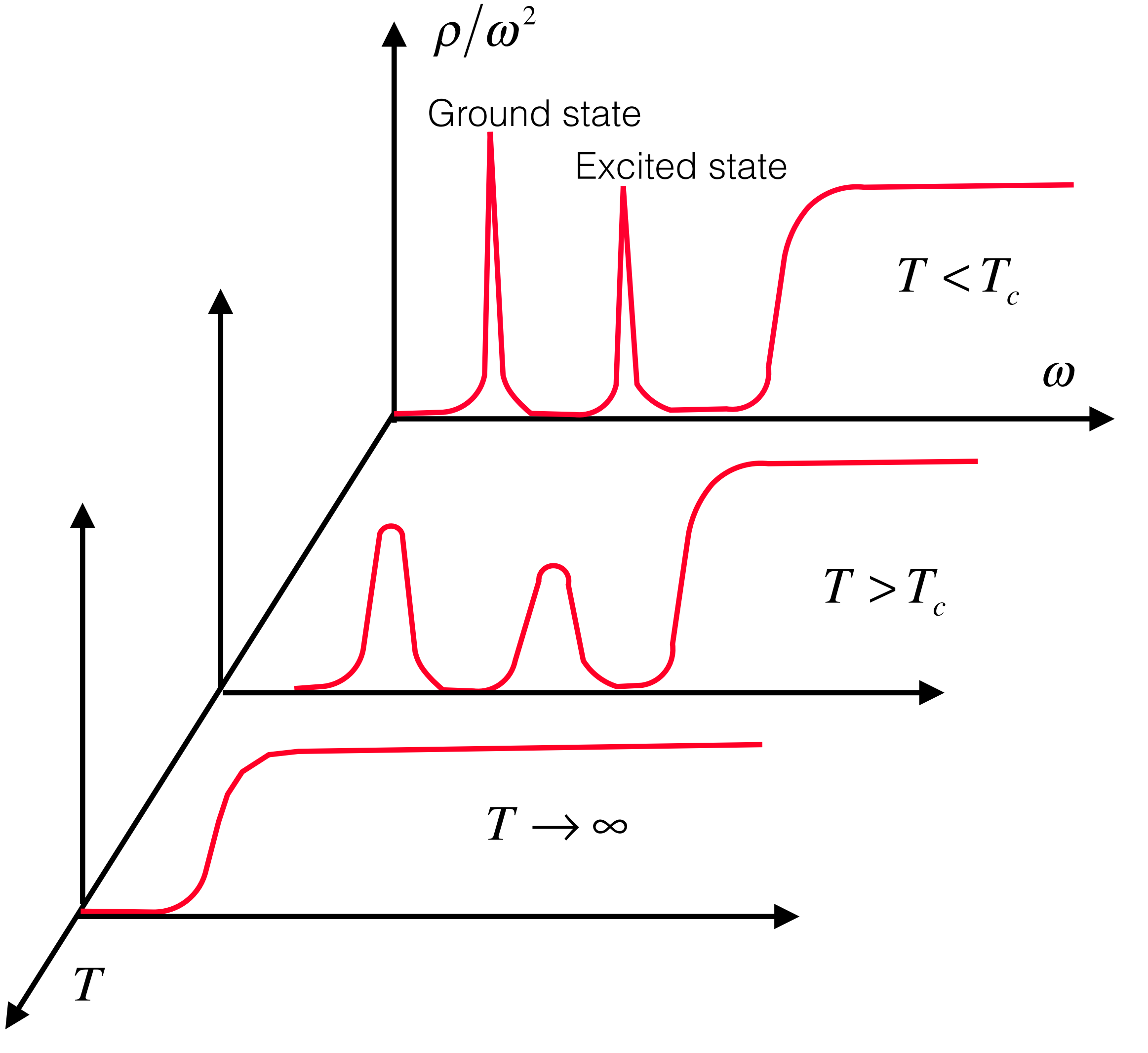
Quarkonia serve as good QGP thermometer.

T. Matsui, H. Satz, Phys. Lett. B178, 416

- What are the “dissociation temperatures” of quarkonia ?
- Do they suffer thermal modification when moving in medium ?

Spectral functions

Spectral functions give all the information about hadrons.



Spectral functions

- Schrödinger equation with potentials
  - ✳ Internal energy ? H. Satz, J.Phys.G32:R25,2006
  - ✳ Free energy ? A. Mocsy and P. Petreczky, Phys. Rev. D 77 (2008) 014501
  - ✳ Complex potential ? M.Laine, et al., JHEP 0703(2007) 054 A. Rothkopf, et al., PRL108,162001
- Spectral function from LQCD

Temporal correlation function relates to spectral function:

$$G_H(\tau,\vec{p}) = \sum_{x,y,z} \exp(-i\,\vec{p}\cdot\vec{x}) \langle J_H(0,\vec{0}) J_H{}^{+}(\tau,\vec{x}) \rangle = \int_0^\infty \frac{d\omega}{2\pi} \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \rho_H(\omega,\vec{p},T)$$

ill-posed!

- ✳ Maximum Entropy Method M. Asakawa, et al., Prog.Part.Nucl.Phys. 46(2001) 445-508
- ✳ New Bayesian Method Y. Burnier and A. Rothkopf, PRL 111 (2013) 18,182003
- ✳ Backus-Gilbert Method B. B. Brandt, et al., Pays. Rev. D93, 054510(2016)
- ✳ Stochastic Analytic Inference H. Ohno, PoS LATTICE 2015
- ✳ Stochastic Optimization Method H.-T. Shu, et al., PoS LATTICE 2015

Correlation functions & Screening mass

- Spatial correlation functions

$$G_H(z,\vec{p}_z,\omega_n)=\sum_{x,y,\tau}\exp(-i\,\tilde{p}\cdot\tilde{x})\langle J_H(0,\vec{0})J_H{}^{+}(\tau,\vec{x})\rangle=\int_{-\infty}^{\infty}\frac{dp_z}{2\pi}\exp(ip_z z)\int_0^{\infty}\frac{d\omega}{\pi}\frac{\omega}{\omega^2+\omega_n{}^2}\,\rho_H(\omega,\vec{p},T)$$

- Exponential decay behavior of spatial correlator at large distance

$$G_H(z,\vec{p}_z,\omega_n)\sim\exp(-zE_{scr})$$

$at\ \vec{p}\to\vec{0},\ E_{scr}\ :\ screening\ mass$

$at\ \vec{p}\to\vec{0}\ and\ T=0,\ E_{scr}=pole\ mass$

In the non-interacting limit: $E_{free}=2\sqrt{(\pi T)^2+m_q{}^2}$

- Dispersion relation

$$E_{scr}{}^2=\vec{p}^2+M^2+\Pi(\vec{p},T)$$

- Absorb thermal effect into *M(T)* and *A(T)*

$$E_{scr}{}^2=A(T)\vec{p}^2+M^2(T)$$

Simulation details

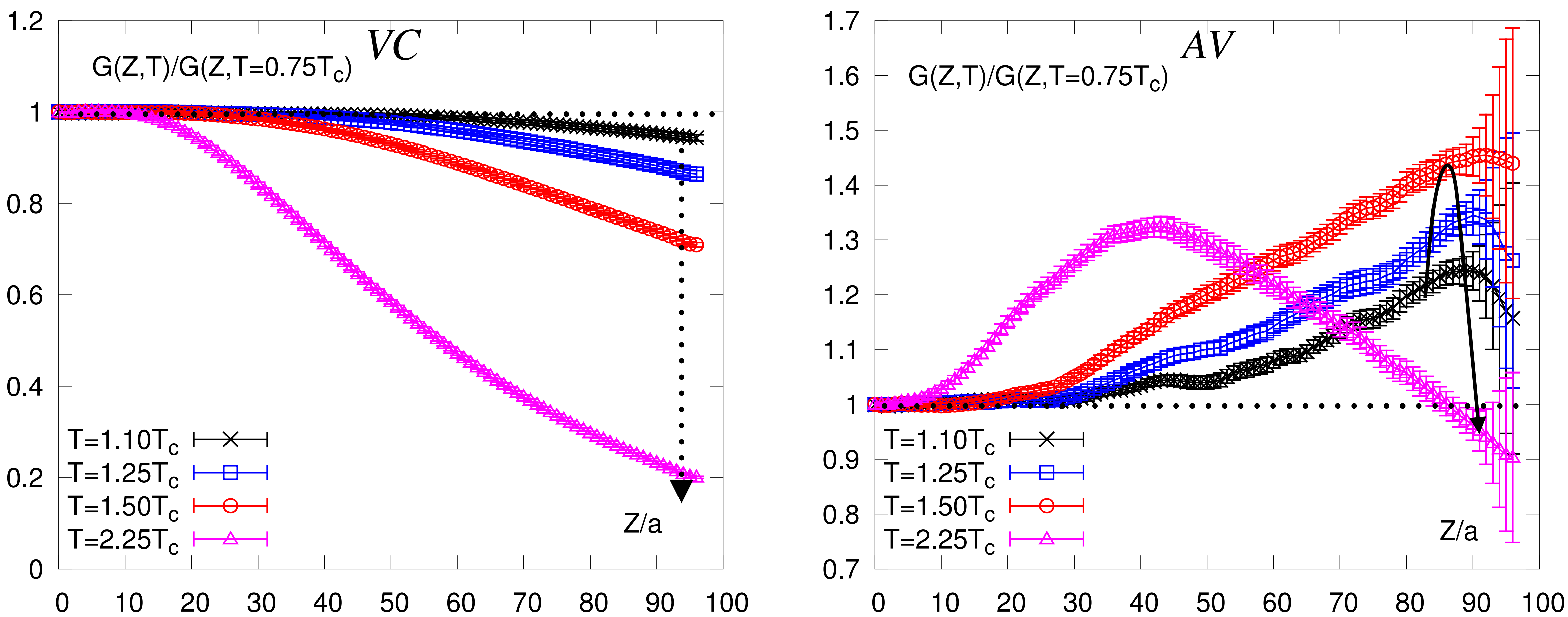
- Isotropic quenched lattices
- Large quenched lattices close to continuum ($aM_Q<<1$)
- $Ns=192$ makes the fitting of screening mass more reliable
- Non-perturbatively Clover-improved Wilson fermions
- Quark masses tuned to reproduce nearly physical J/ψ mass and Υ mass

[For the tuning of quark masses, see Hauke Sandmeyer's talk today at 17:00~17:20]

- $0 \leq |\boldsymbol{p}| \leq 3.17$GeV
  - non-zero momenta (1 source, δG/Ḡ ~1.5% at the middle point in the vector channel)
  - zero momentum (~5 sources, δG/Ḡ ~2 times smaller)

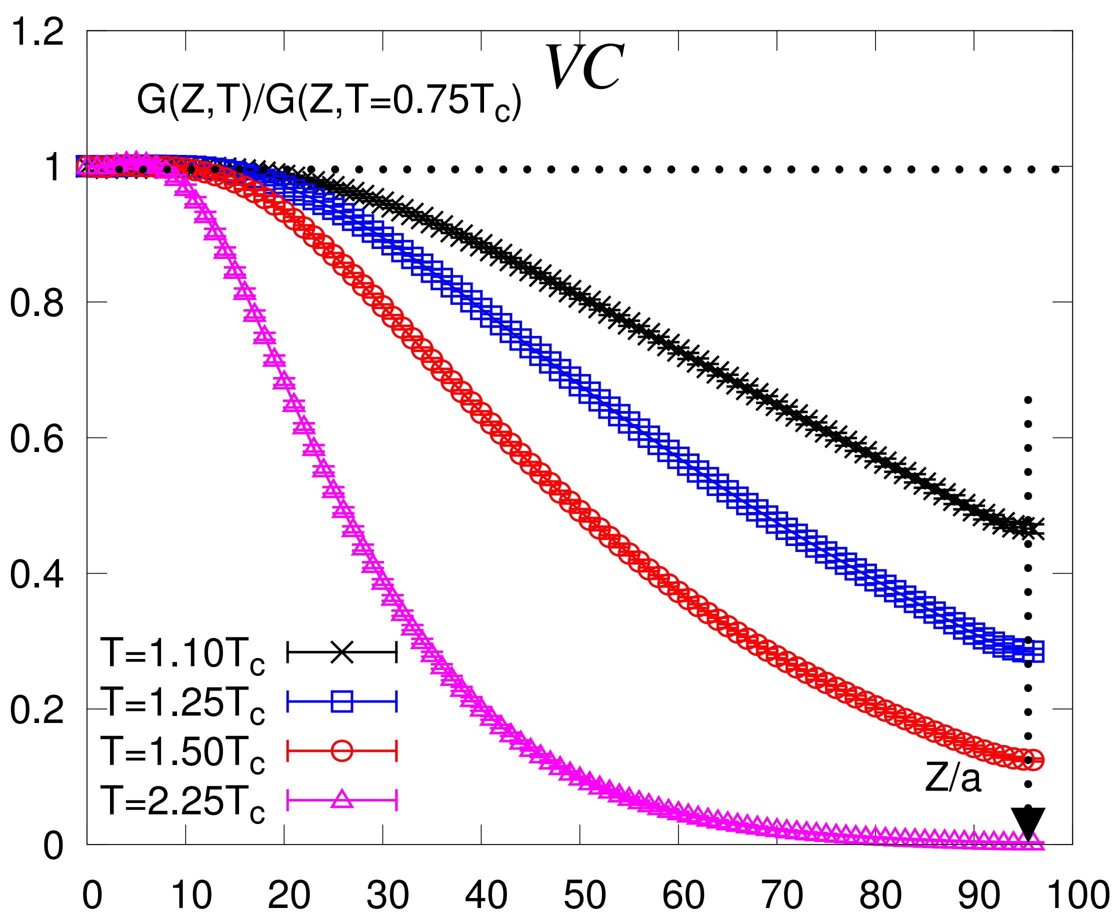
β	a^{-1}	κ	N_σ	N_τ	T/T_c	#conf
7.793	22.8GeV	$0.13221(c\bar{c})$ $0.12798(b\bar{b})$	192	96	0.75	218
				64	1.10	248
				56	1.20	190
				48	1.50	210
				32	2.25	235

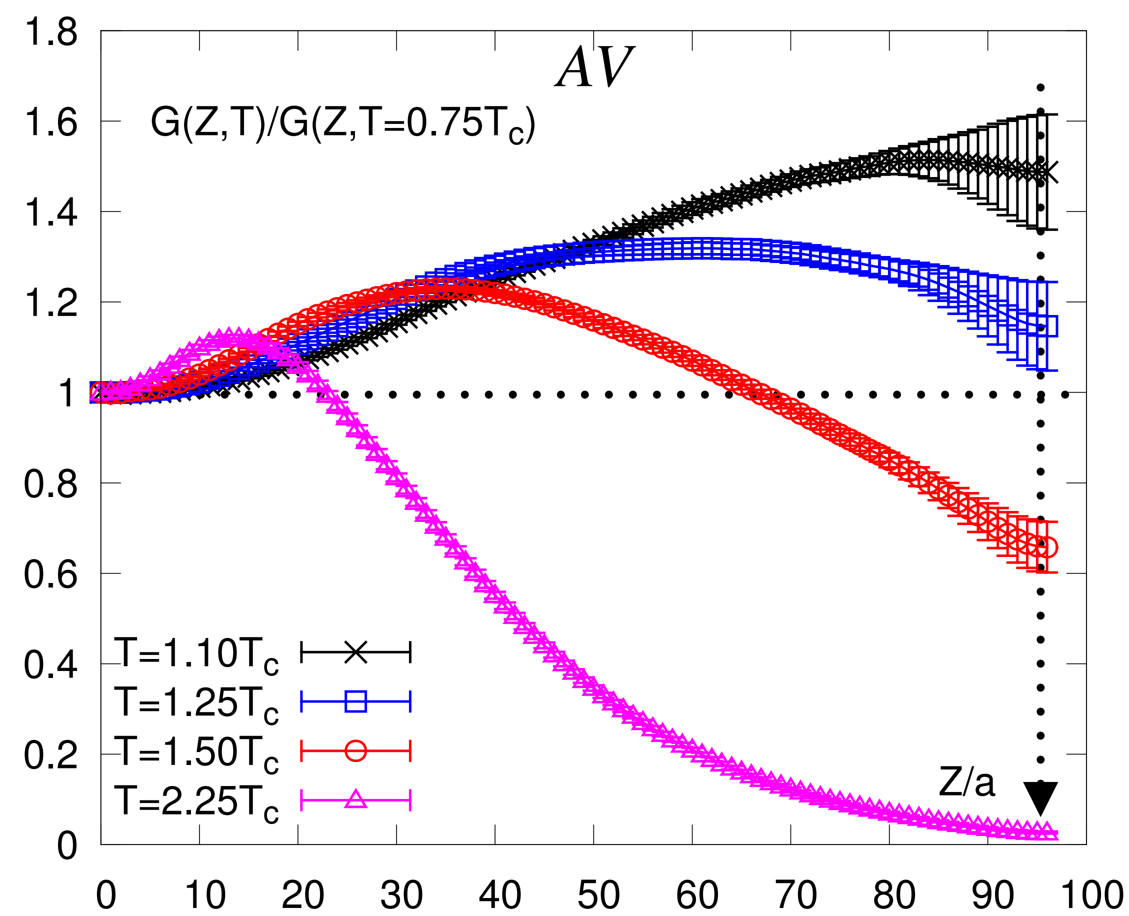
Ratio of correlators for $b\bar{b}$



- As *T* increases, ratios in the *VC* channel decrease and are always smaller than 1 => $M_{scr}(T)$ increases monotonically; $M_{scr}(T) > M_{scr}(0.75T_c)$
- As *T* increases, non-monotonic behavior of ratios at the middle point is observed in the *AV* channel.
- Need more statistics to improve the signal-noise ratio in the *AV* channel.

Ratio of correlators for $c\bar{c}$





As *T* increases:

- similar situation has been found in the *VC* channel as in the case of $b\bar{b}$ but the deviation from unity is larger.
- ratios in the *AV* channel drop from larger than 1 to smaller than 1 => at $T=1.10,\ 1.25T_c$, $M_{scr} < M_{scr}(0.75T_c)$; at $T=1.50,\ 2.25T_c$, $M_{scr} > M_{scr}(0.75T_c)$

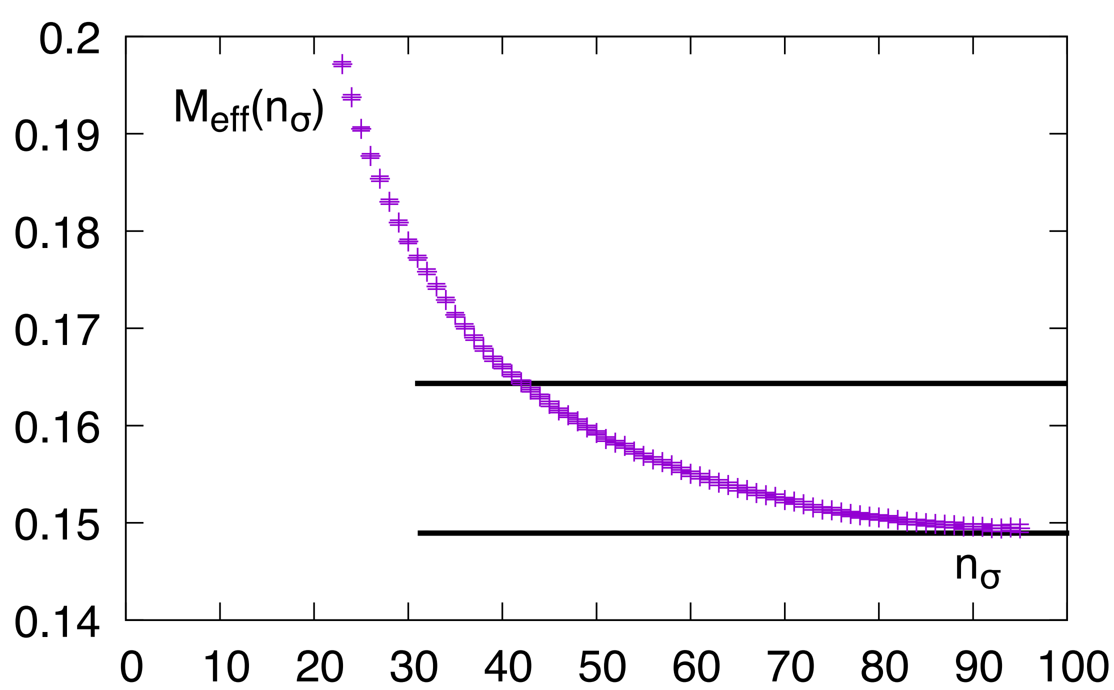
Screening mass—fit ansatz

Spatial correlators:

$$G(n_\sigma) = A_1 \cosh\left(M_{scr1}(n_\sigma - N_\sigma/2)\right) + A_2 \cosh\left(M_{scr2}(n_\sigma - N_\sigma/2)\right) + \cdots$$

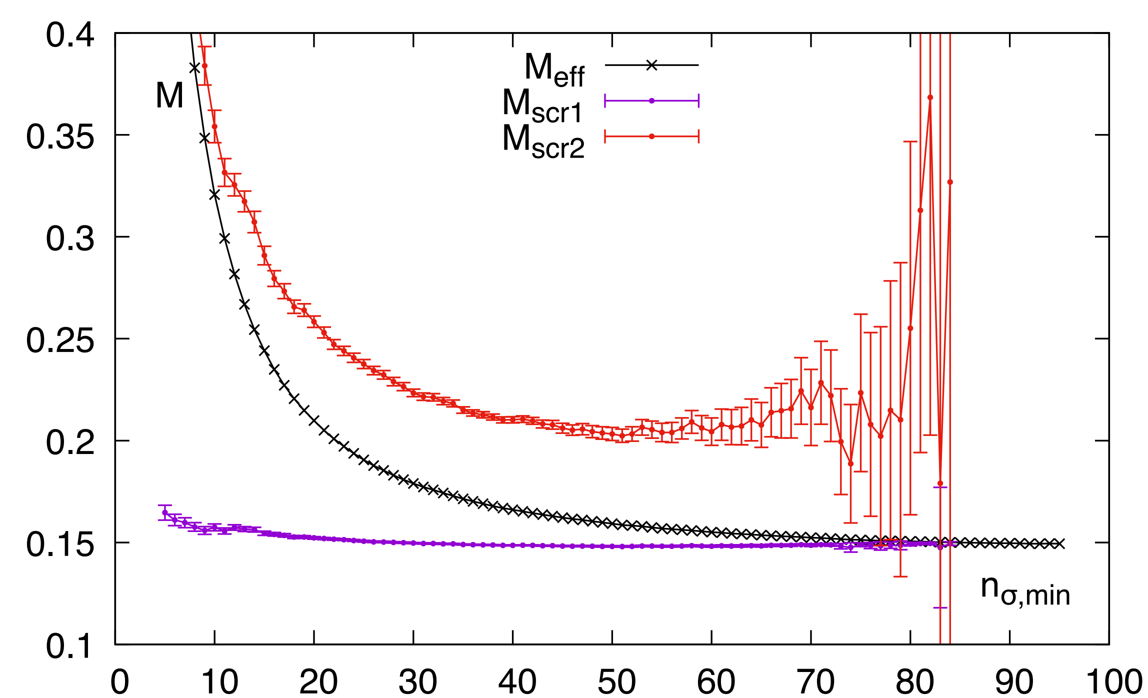
one-state ansatz—>Effective mass

$$\frac{G(n_\sigma)}{G(n_\sigma+1)} = \frac{\cosh\left(m_{eff}(n_\sigma - N_\sigma/2)\right)}{\cosh\left(m_{eff}(n_\sigma + 1 - N_\sigma/2)\right)}$$

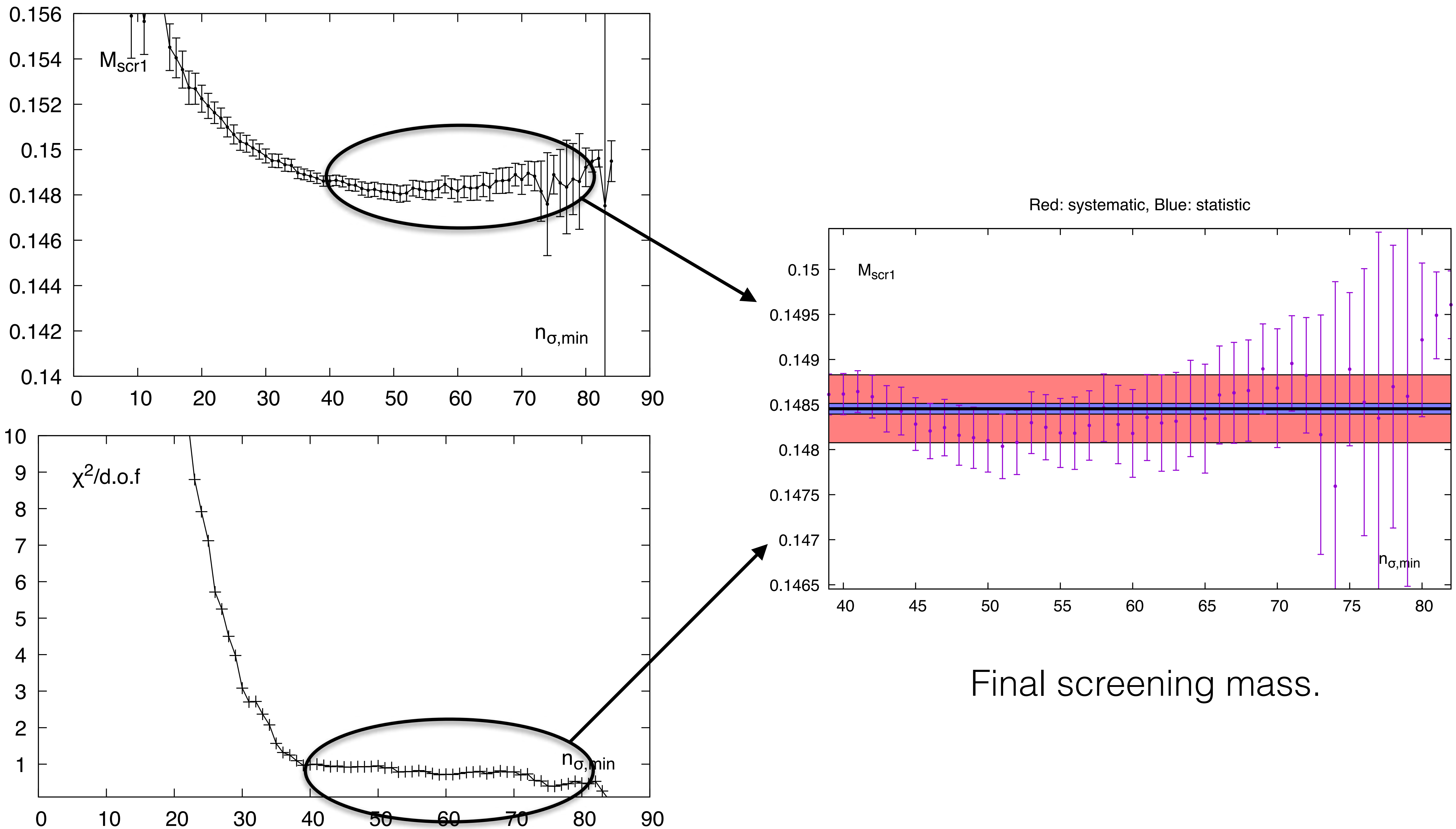


two-state ansatz—>screening mass

$$G(n_\sigma) = A_1 \cosh\left(M_{scr1}(n_\sigma - N_\sigma/2)\right) + A_2 \cosh\left(M_{scr2}(n_\sigma - N_\sigma/2)\right)$$



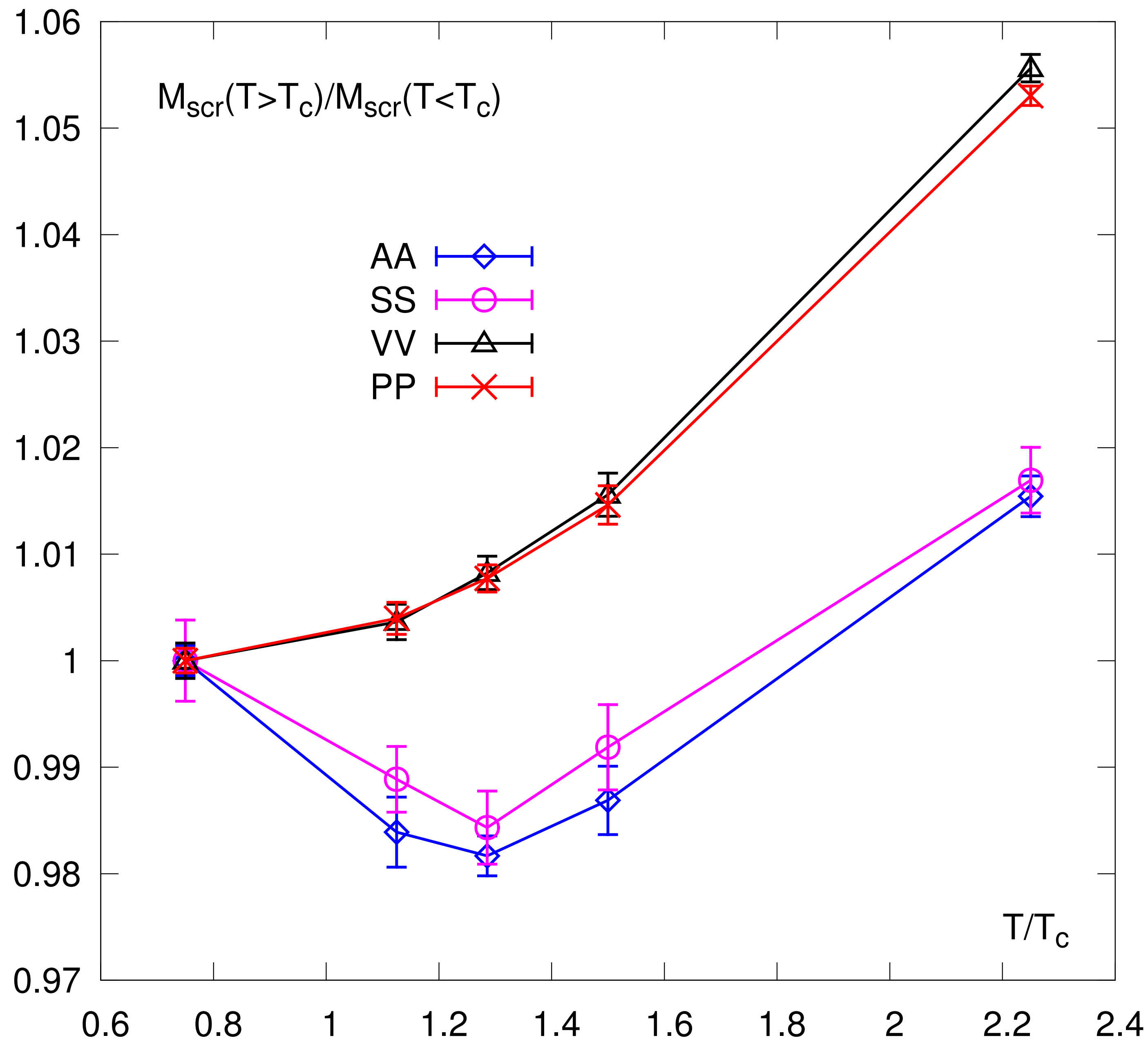
Screening mass—determine the plateau



Final screening mass.

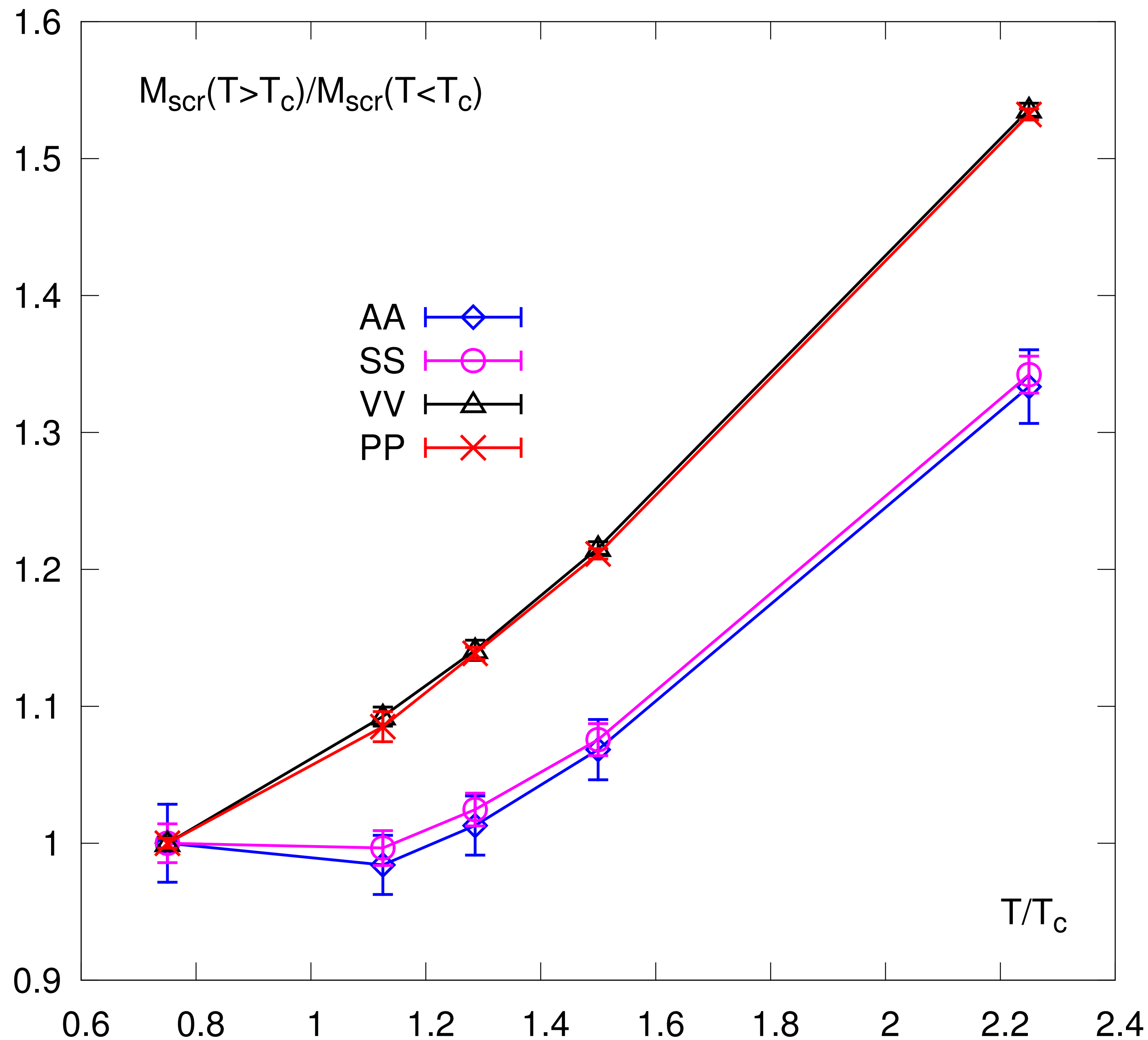
Determine the interval of the plateau.

Screening mass of $b\bar{b}$ at different temperatures



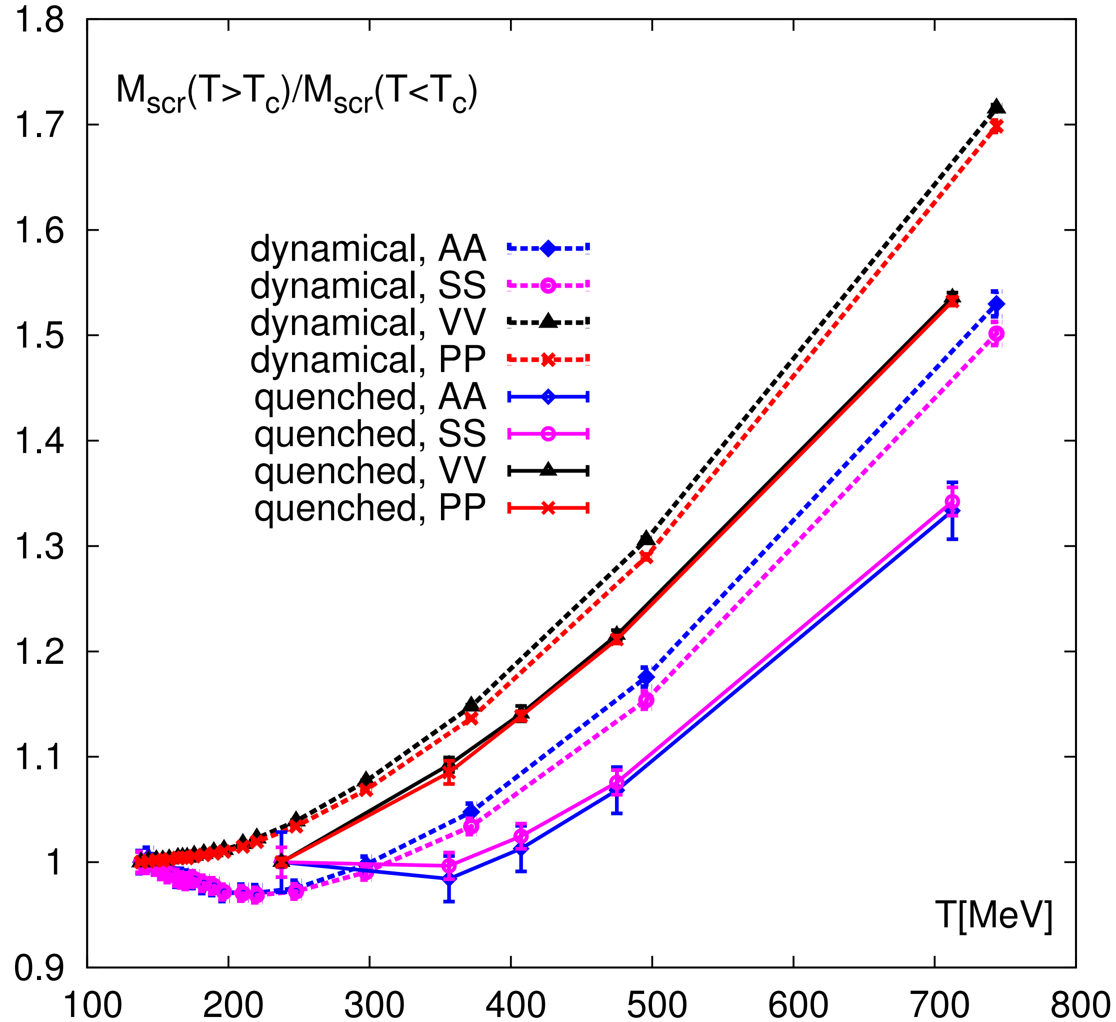
- Ratios in the *AV v.s. SC* channel, *VC v.s. PS* channel are similar respectively.
- The screening masses of s-wave states increase monotonically by ~5.6% at *2.25*T_c while for p-wave they drop first and then go up.

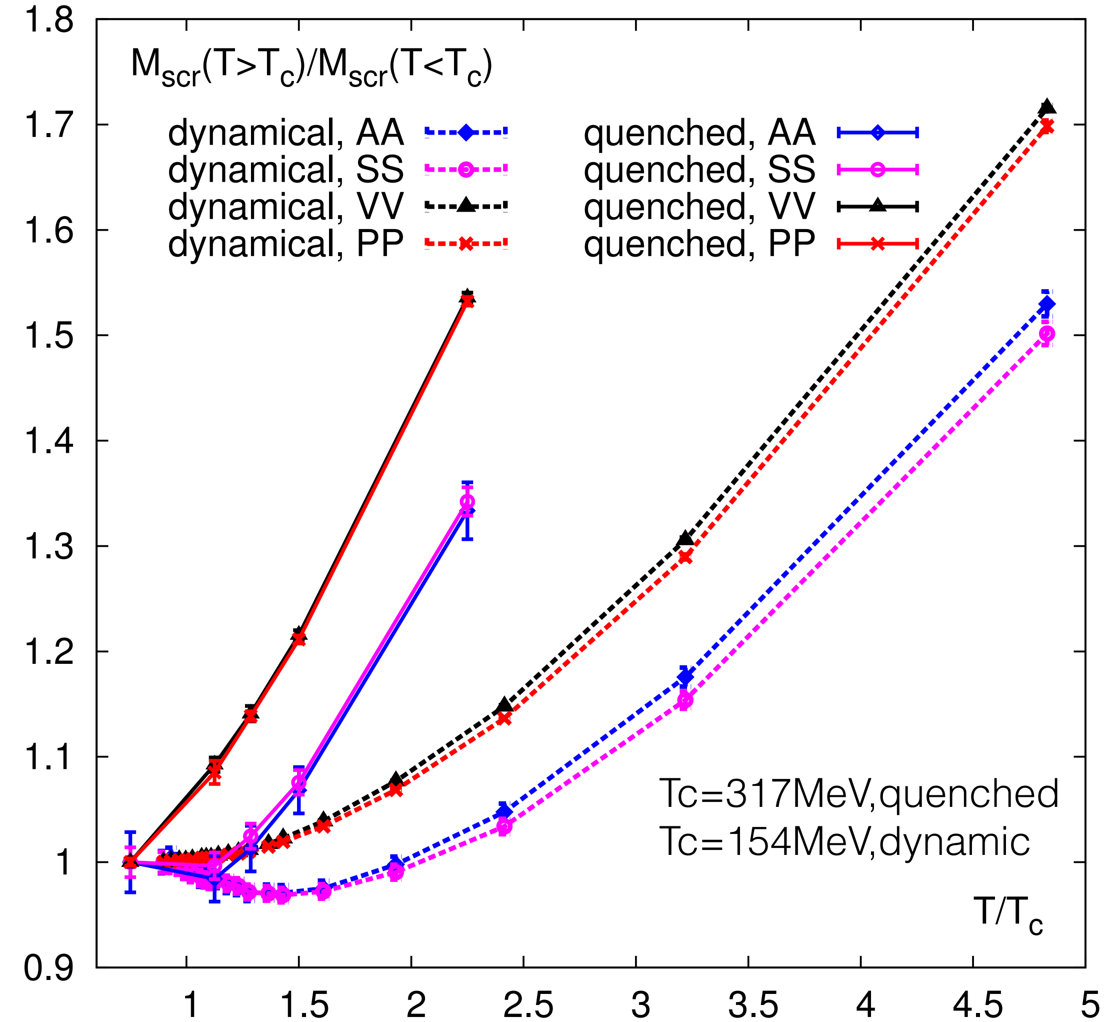
Screening mass of $c\bar{c}$ at different temperatures



- Similar case is observed as in the case of bottomonia.
- The screening masses of s-wave states increase by ~54% at *2.25*T_c. Much larger than that in the case of bottomonia (5.6%).

Screening mass—Quenched v.s. 2+1 HISQ

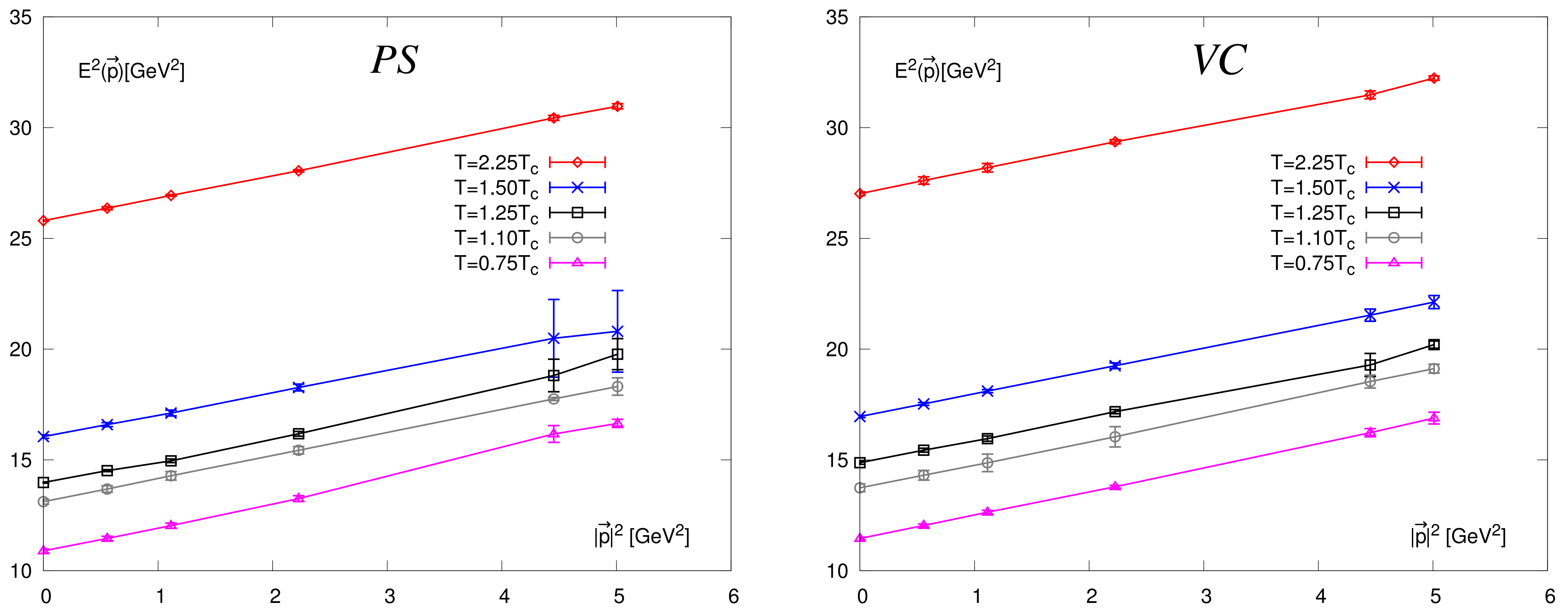




Nf=2+1, HISQ from: Phys.Rev.D91,054503(2015)

- Our quenched calculations and 2+1 HISQ calculations show the similar *T* dependence of the screening masses.
- In our quenched calculations, the screening masses for p-waves have a dip at $1.10T_c$ while in dynamic QCD the dip is at $1.43T_c$.

Dispersion relation from the screening mass of $c\bar{c}$



$$E_{scr}{}^2 = A(T)\vec{p}^2 + M^2(T)$$

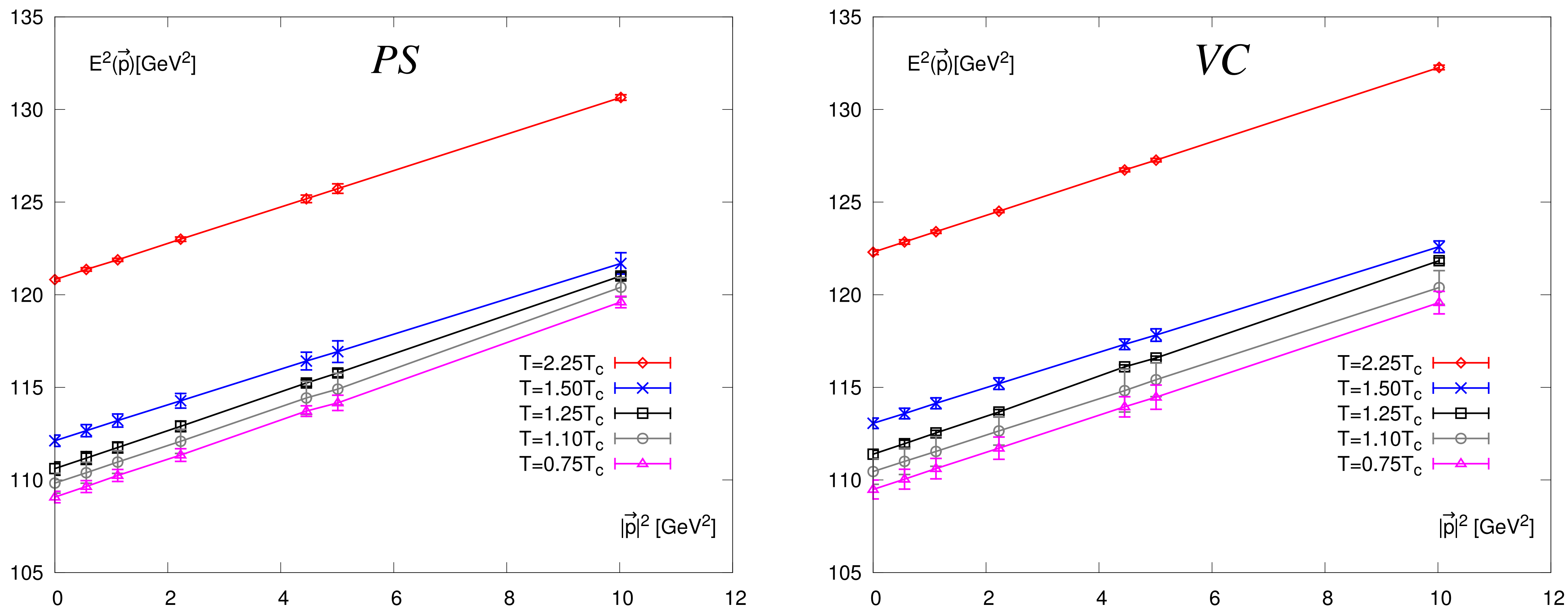
- Dispersion relation for s-wave states remains unmodified for charmonia as *A(T)~1*.

See also: A. Ikeda, et al., Phys. Rev. D95. 014504

Masakiyo Kitazawa's talk at 16:40-17:00

- The reason could be that the largest momentum 3.17GeV is still less than the masses of charmonia (~3.5GeV)

Dispersion relation from the screening mass of $b\bar{b}$



$$E_{scr}{}^2 = A(T)\vec{p}^2 + M^2(T)$$

- Similar situation has been observed as in the case of charmonia.

For non-relativistic quarks, see: G. Aarts, et al., JHEP 1303(2013) 084

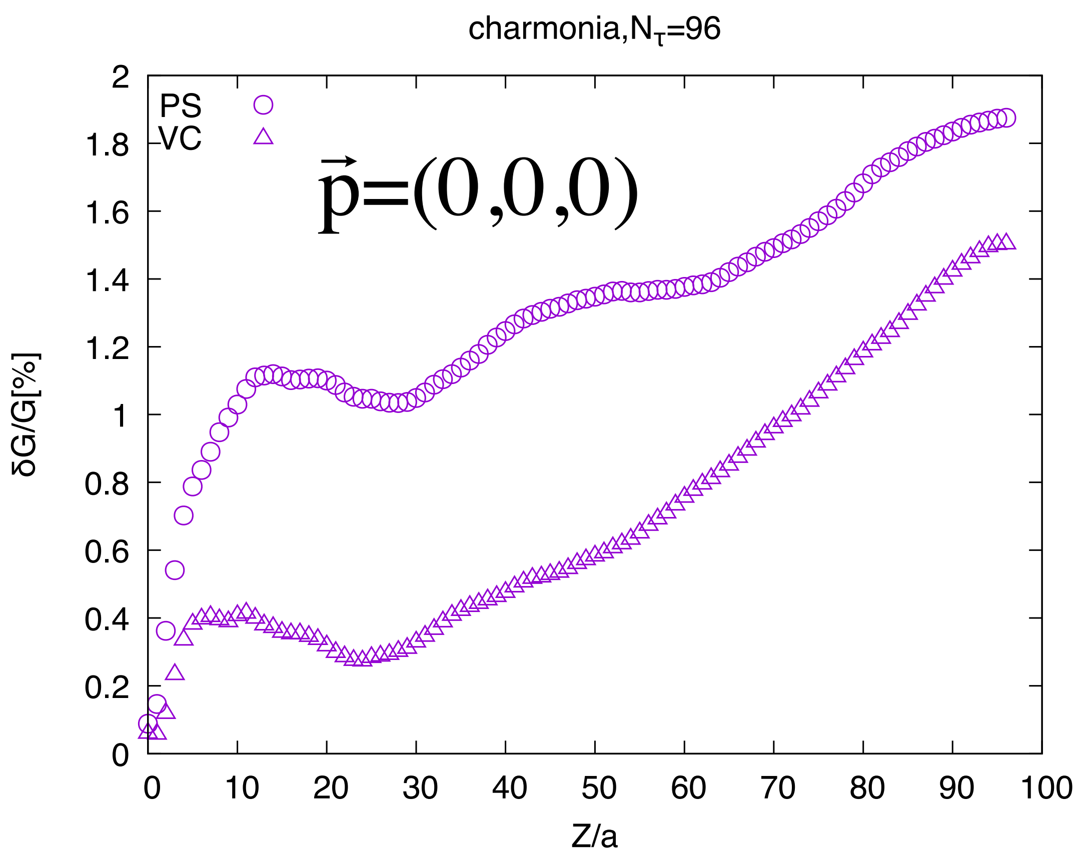
Summary

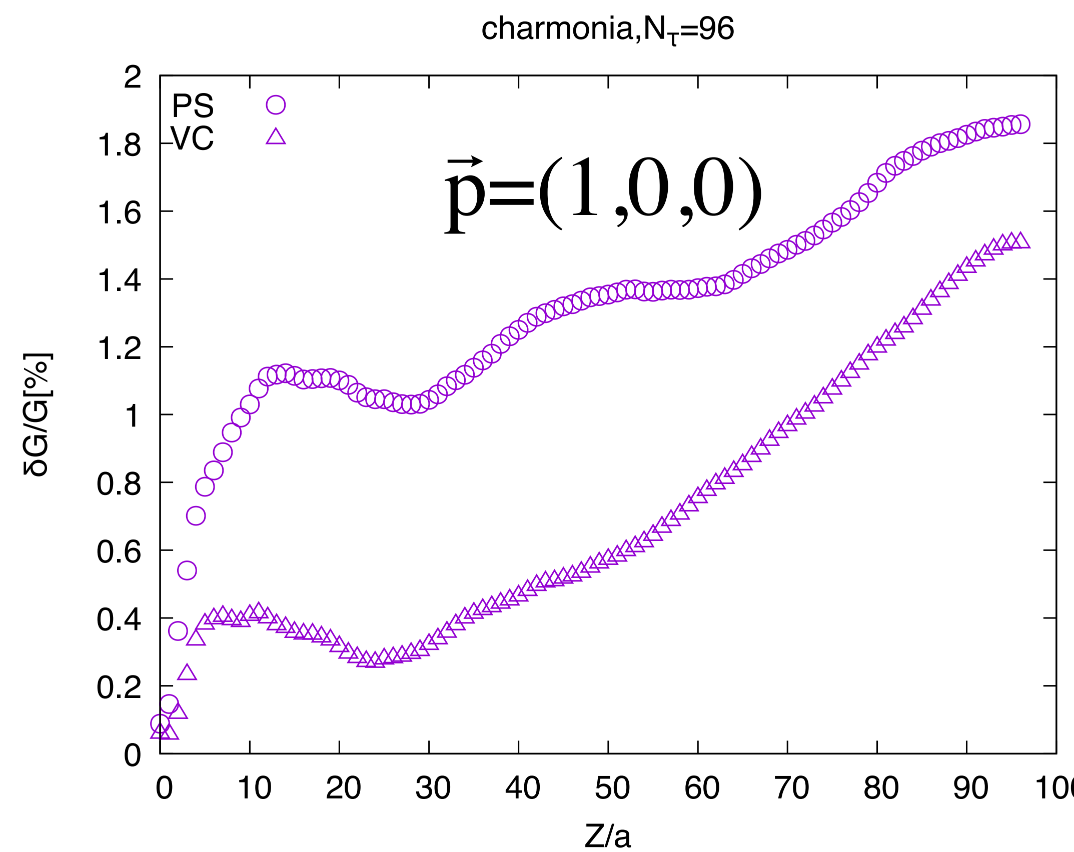
We have performed simulations on large quenched lattices to calculate the spatial Euclidean correlation functions.

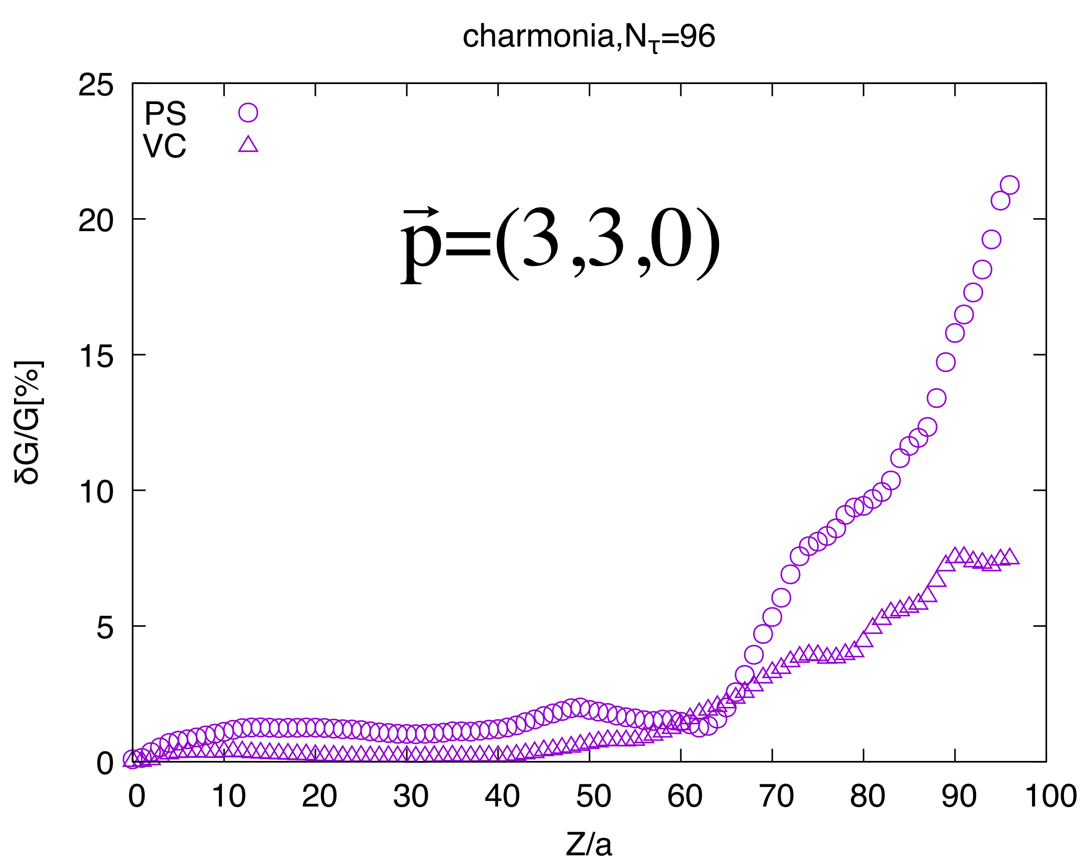
- M_{src} of s-wave states for both $b\bar{b}$ and $c\bar{c}$ increase monotonically in T. For $b\bar{b}$, $M_{src}(2.25T_c)/M_{src}(0.75T_c)$ -1 is by 5.6% while for $c\bar{c}$ by 54%.
- M_{src} of p-wave states for both $b\bar{b}$ and $c\bar{c}$ increase non-monotonically in T.
- Our quenched calculations and 2+1 HISQ calculations show the similar change tendency of M_{src}.
- In both our quenched simulations and 2+1 HISQ simulations, M_{src} of p-wave states have a dip but they appear at different T.
- Dispersion relation in our quenched simulations seems to be not modified in medium when $p < M_{src}(p=0)$.

Thanks!

Back-up. relative error at different momenta

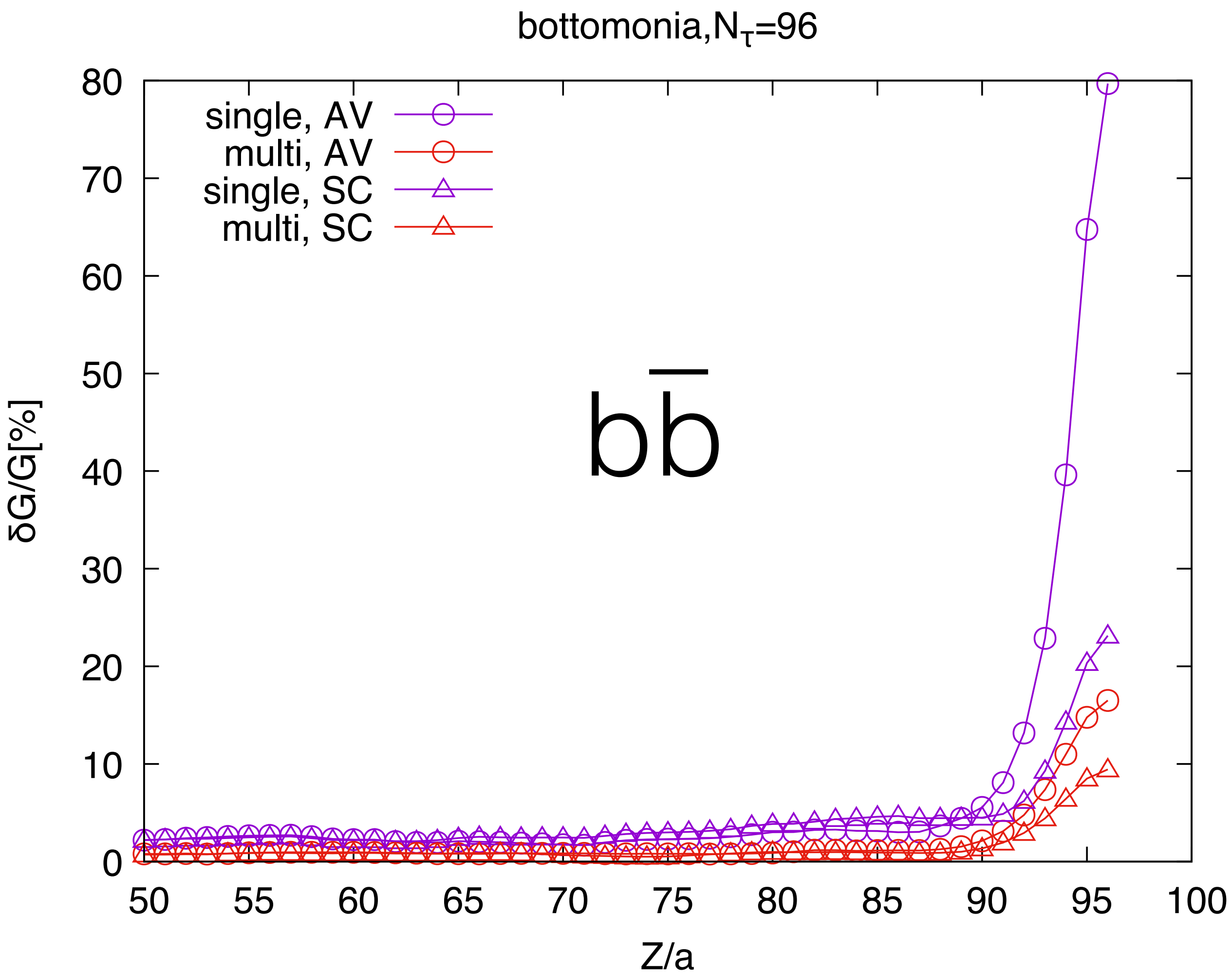


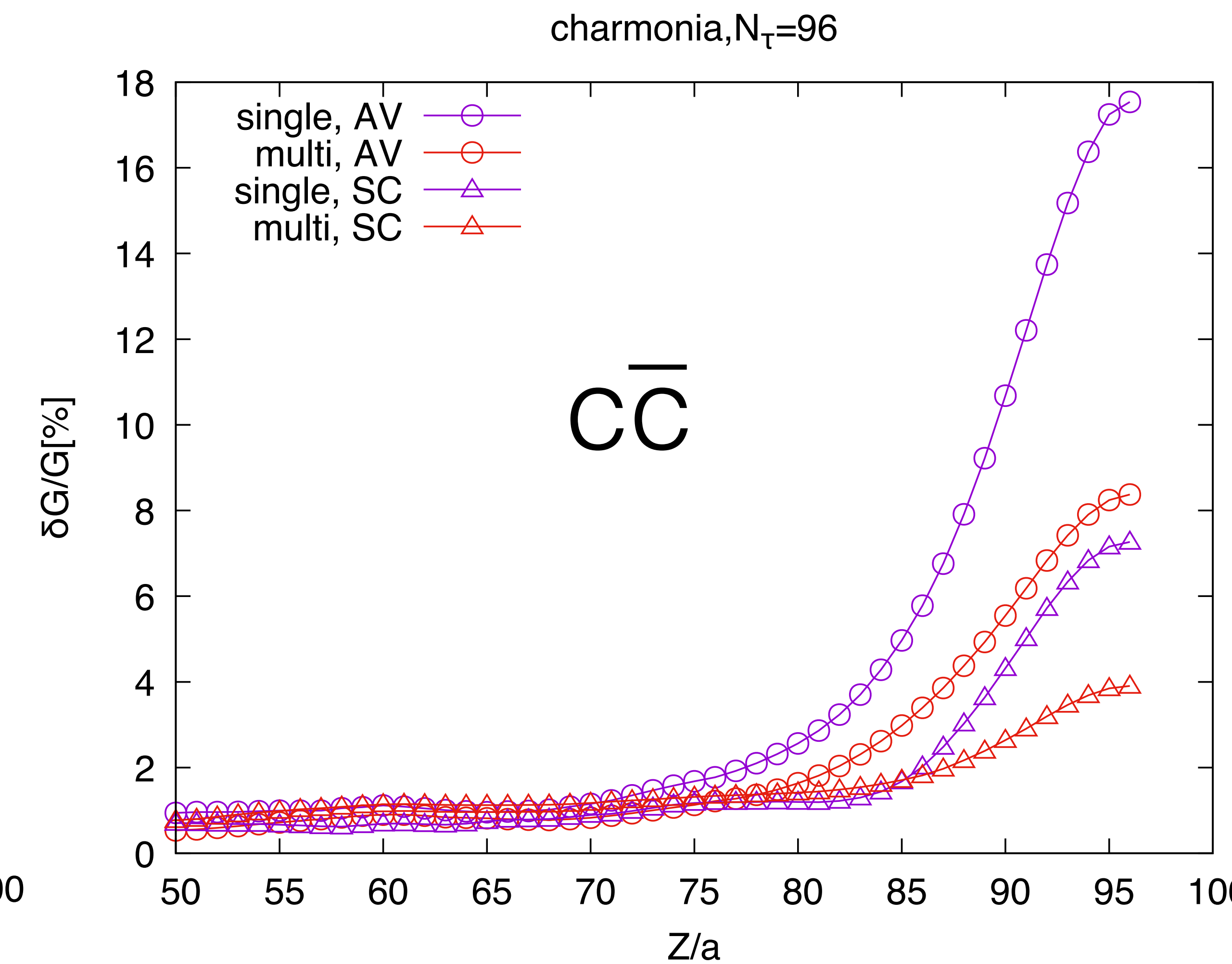




- The error is small at small momenta: around 1.5% in VC channel, 1.8% in PS channel
- The error becomes larger at the largest momenta: around 7% in VC channel, 22% in PS channel

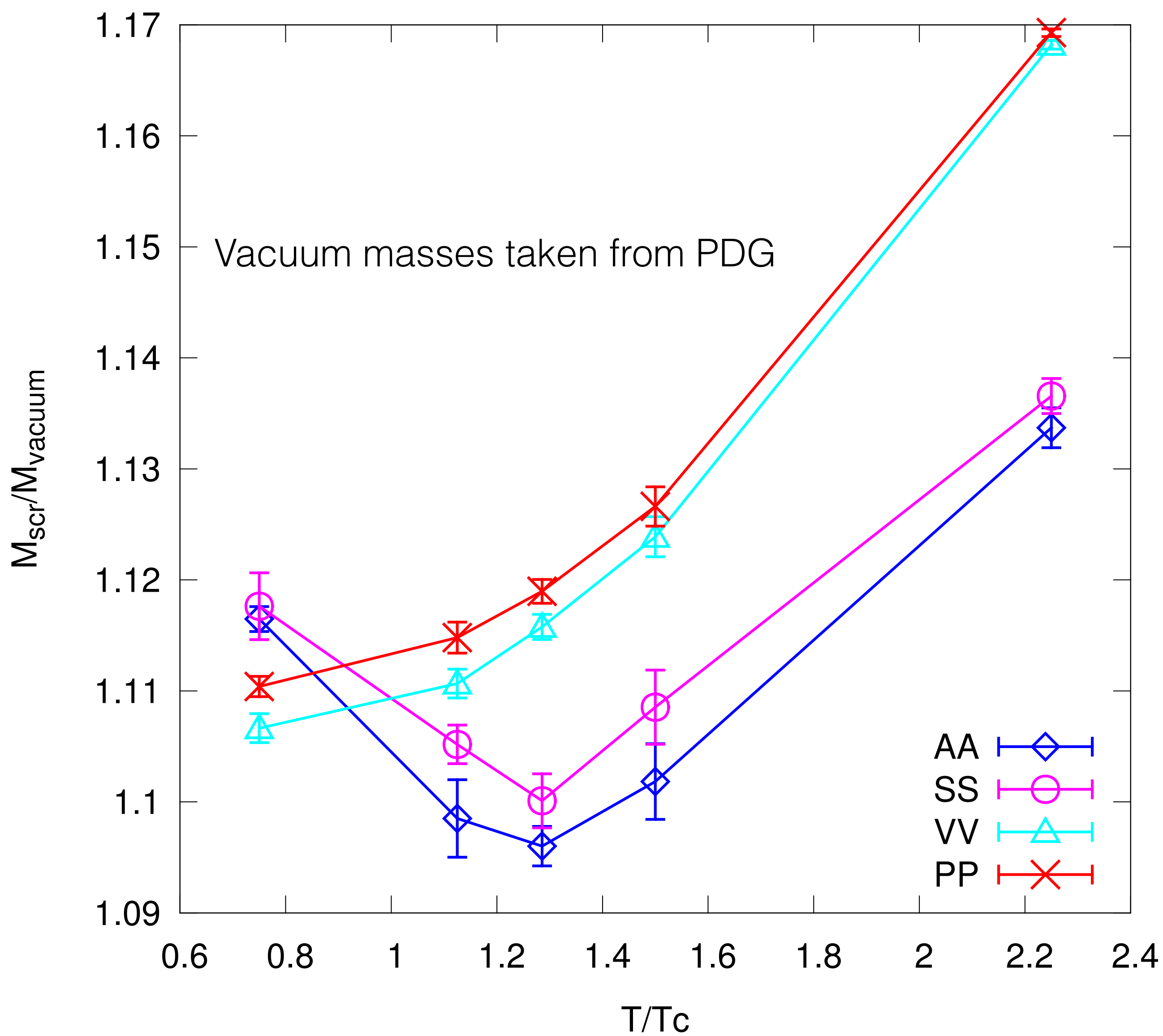
Back-up. single source v.s. multiple sources





- The relative errors in p-wave are much larger than those in s-wave
- The error is much reduced when multi-sources in the measurement are used

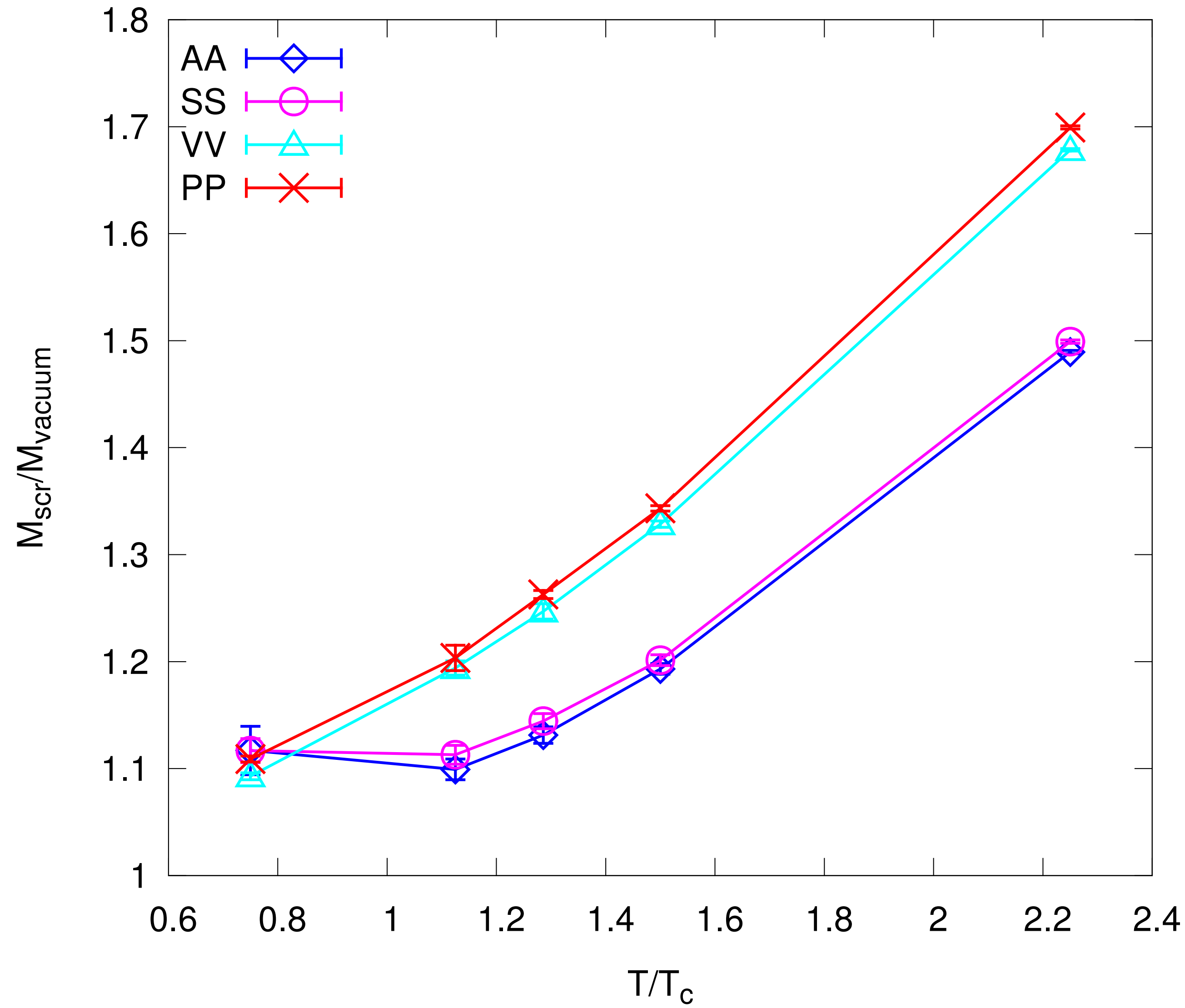
Screening mass of $b\bar{b}$ at different temperatures



Refer to Hauke's talk about the mistuning of the quark masses.

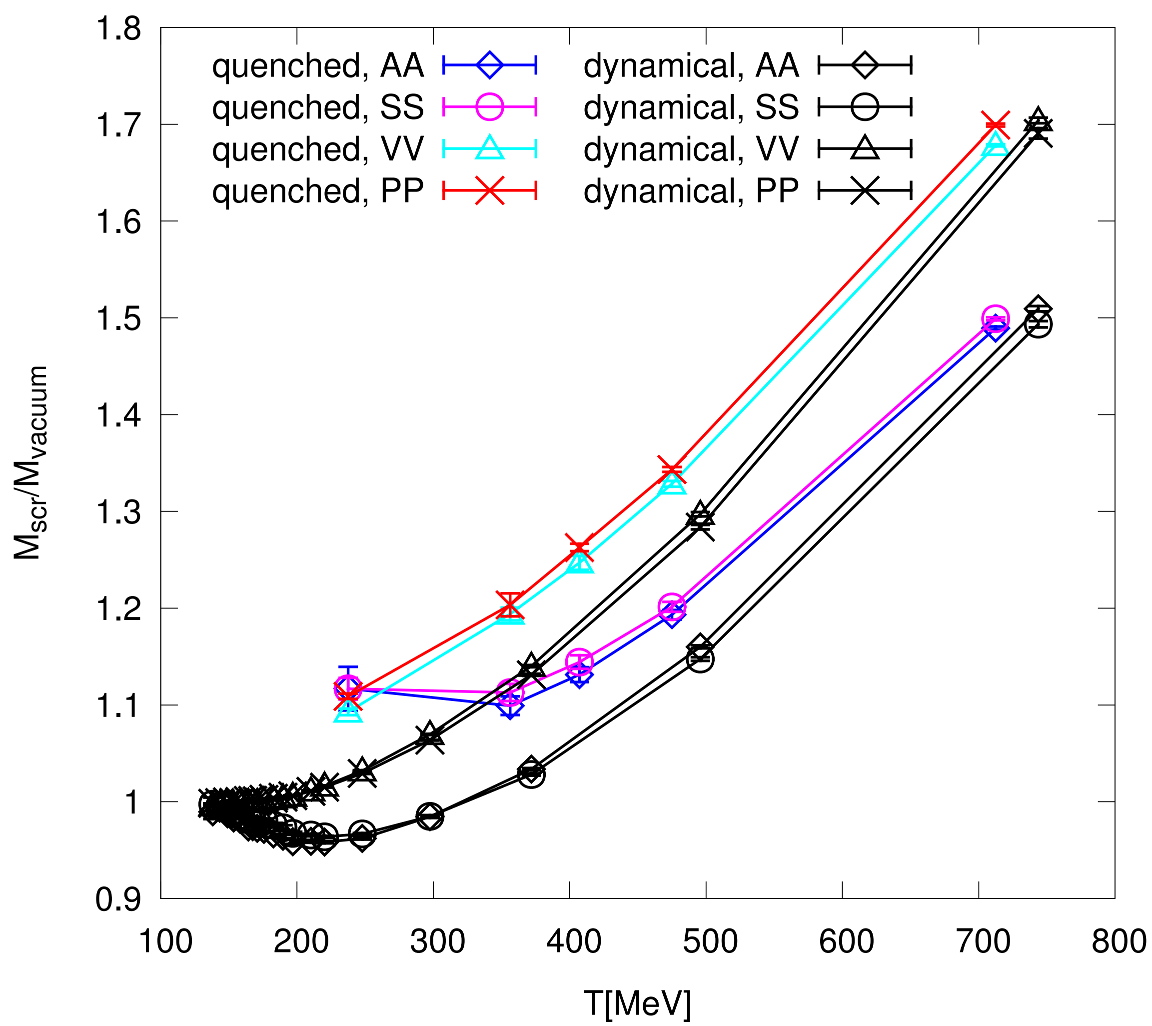
- The screening masses for s-wave increase monotonically by 5.6% at 2.25Tc while for p-wave they drop first and then go up.

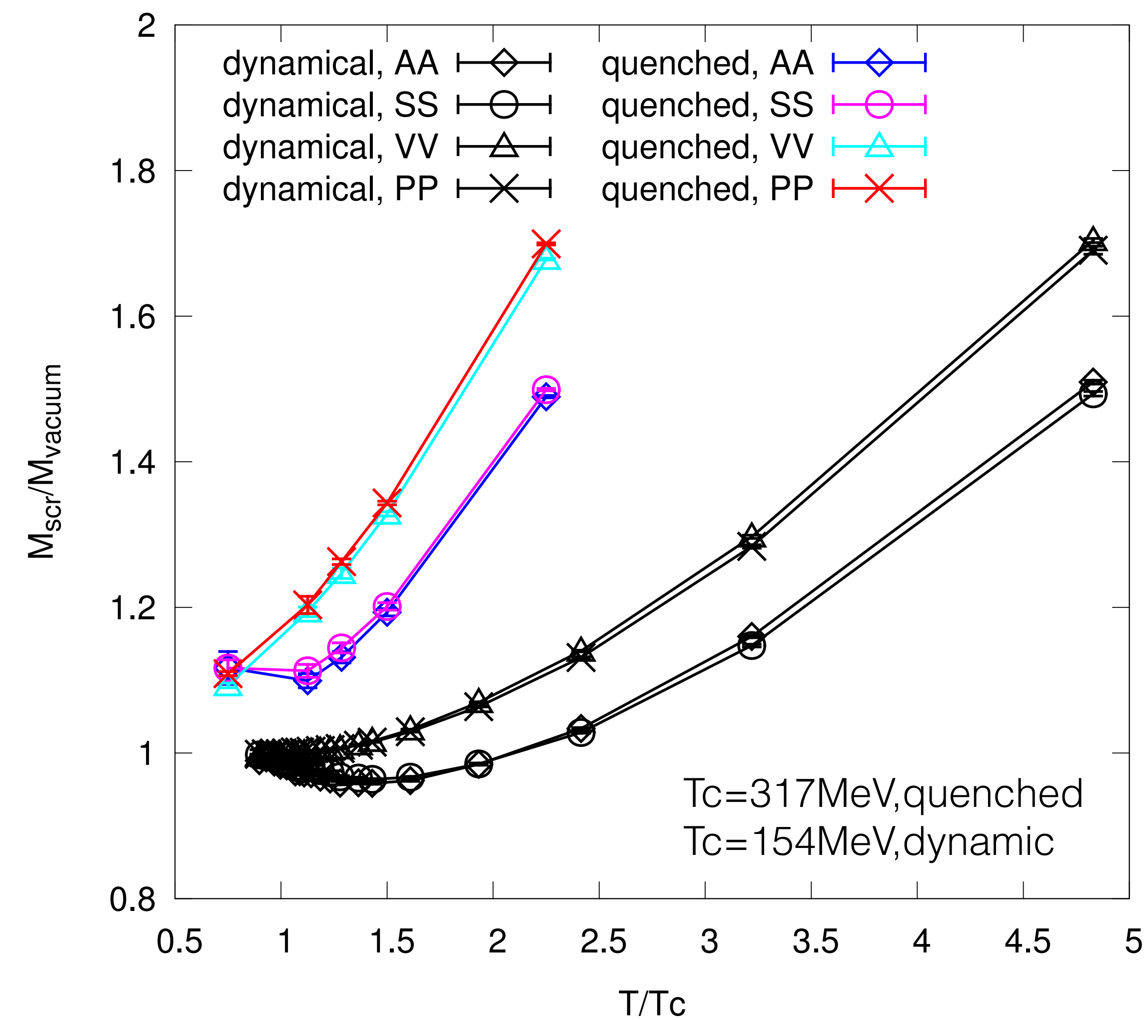
Screening mass of $c\bar{c}$ at different temperatures



- Similar changing pattern was observed as in the case of bottomonia.
- The screening masses for s-wave increase by ~54% at 2.25Tc. Much larger than that in bottomonia.

Screening mass at different temperatures





Nf=2+1, HISQ from: Phys.Rev.D91,054503(2015)

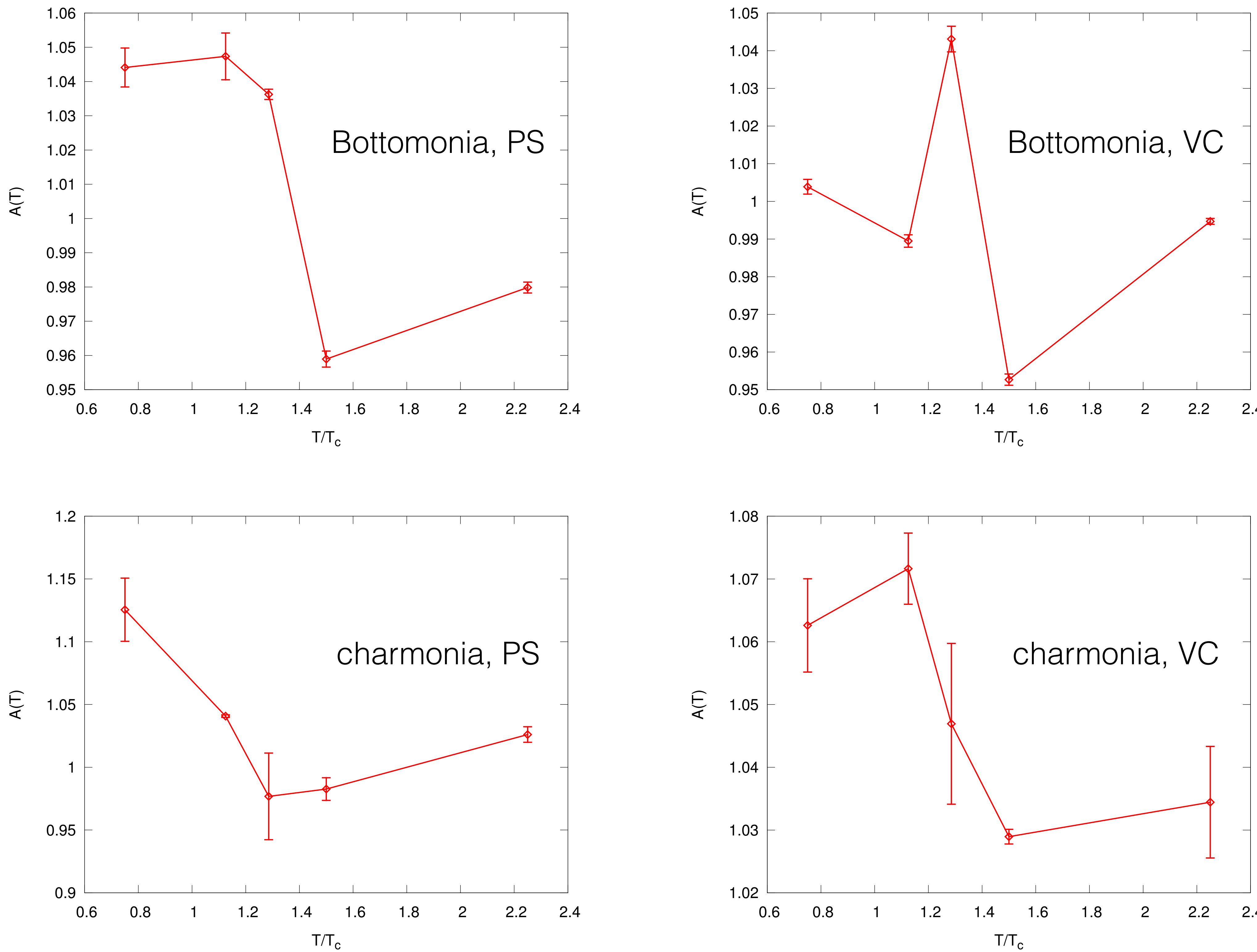
- Our quenched calculations give larger screening masses than 2+1 HISQ calculations give.
- In our quenched calculations, the screening masses for p-waves have a dip at 1.10Tc while 2+1 HISQ calculations have one at 1.43Tc.

Back-up

$$\langle M_{scr1} \rangle \equiv \left(\sum_{n_{\sigma,min}=n_{lower}}^{n_{upper}} \frac{1}{(\delta M_{scr1,fit}(n_{\sigma,min}))^2} \right)^{-1} \sum_{n_{\sigma,min}=n_{lower}}^{n_{upper}} \frac{M_{scr1,fit}(n_{\sigma,min})}{(\delta M_{scr1,fit}(n_{\sigma,min}))^2}$$

$$\delta \langle M_{scr1} \rangle_{stat} \equiv \sqrt{\left(\sum_{n_{\sigma,min}=n_{lower}}^{n_{upper}} \frac{1}{(\delta M_{scr1,fit}(n_{\sigma,min}))^2} \right)^{-1}}$$

$$\delta \langle M_{scr1} \rangle_{syst} \equiv \sqrt{\langle (M_{scr1,fit} - \langle M_{scr1,fit} \rangle)^2 \rangle}.$$


Bottomonia, PS
Bottomonia, VC
charmonia, PS
charmonia, VC
A(T)
T/Tc
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
1.2
1.15
1.1
1.05
1
0.95
0.9
1.08
1.07
1.06
1.05
1.04
1.03
1.02
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4