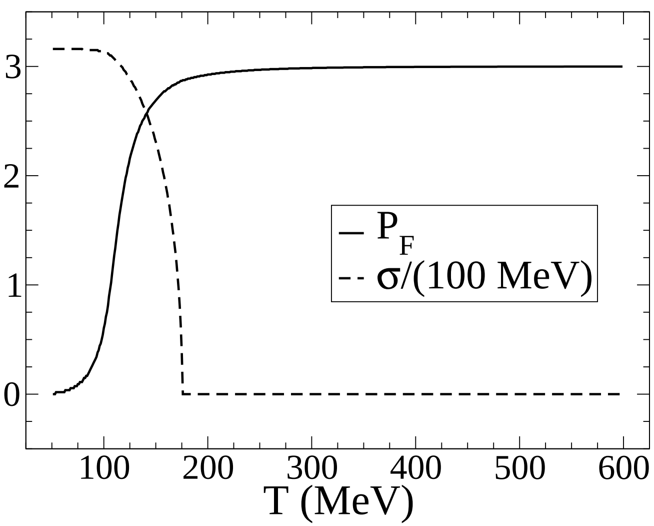
Heavy Quark bound states in a deconfined Quark-Gluon Plasma

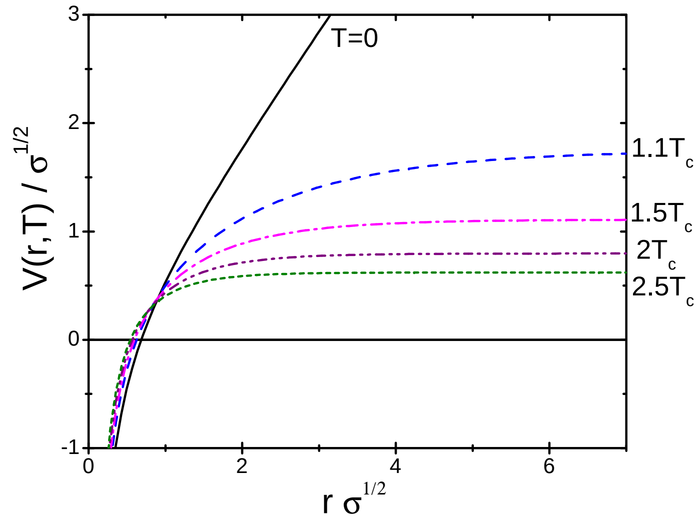
Stefano Carignano

December 2008

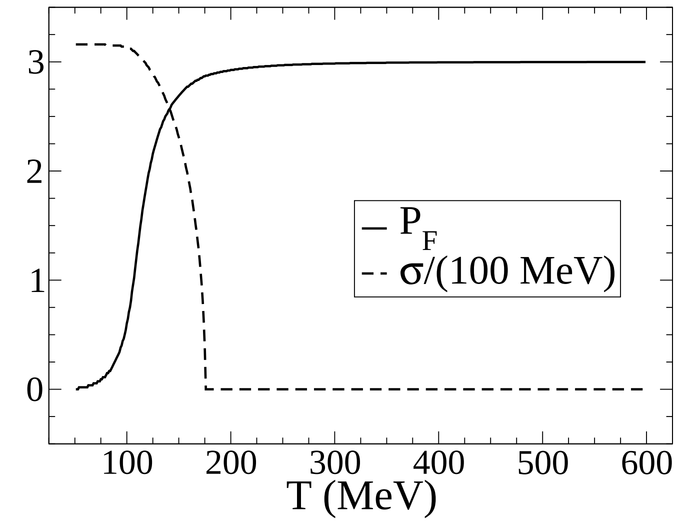
Intro: Quark Gluon Plasma

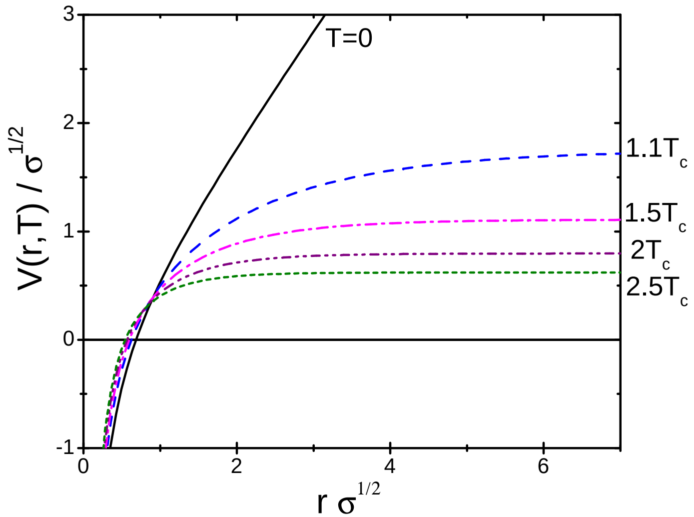
- Lattice QCD: phase transition





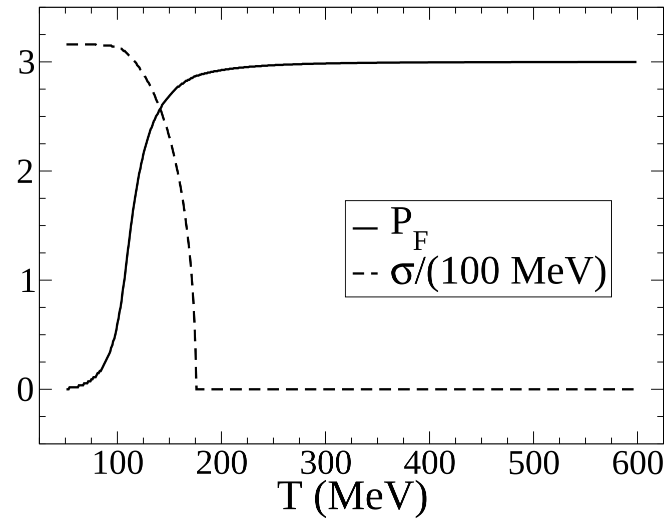
- Lattice QCD: phase transition

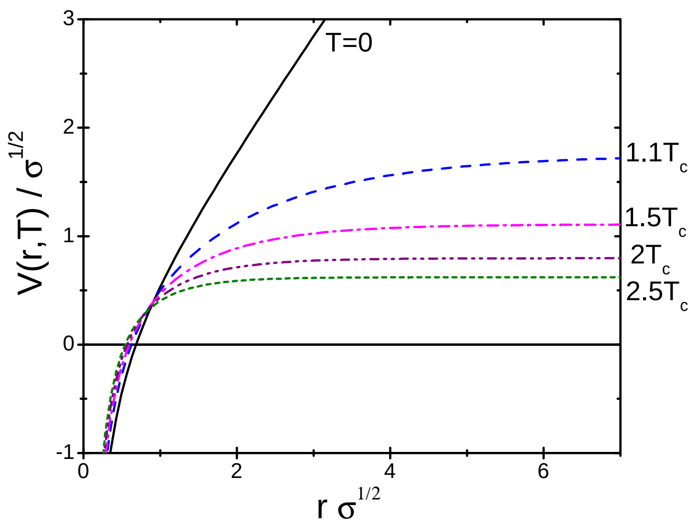




Critical temperature T_c

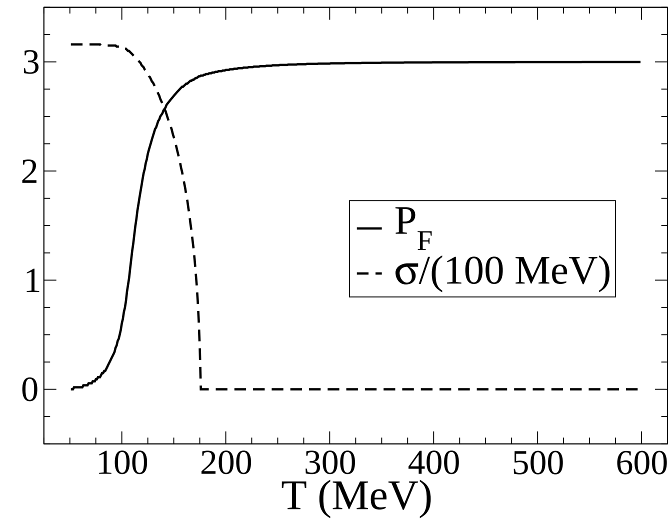
- Lattice QCD: phase transition

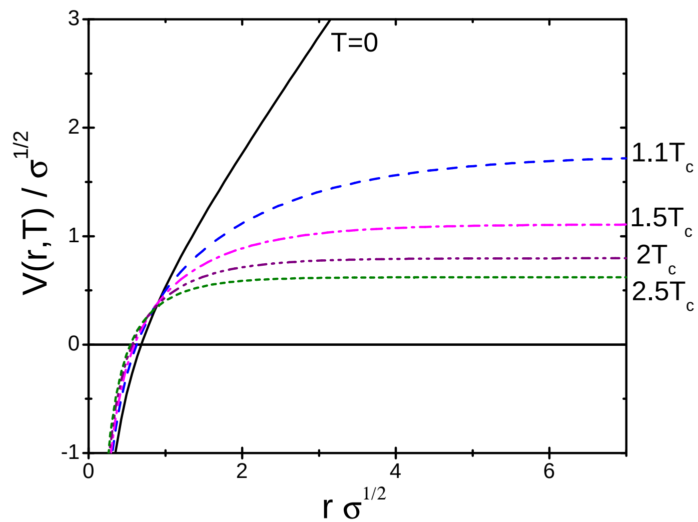




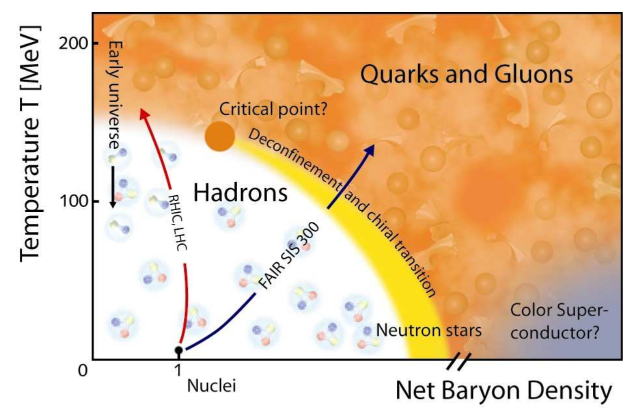
Critical temperature T_c
$\longrightarrow$ Deconfinement

- Lattice QCD: phase transition



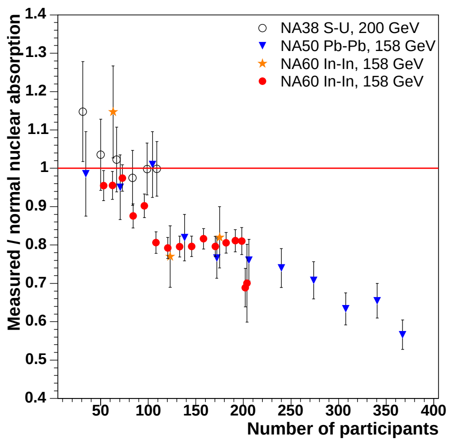


Critical temperature T_c
$\longrightarrow$ Deconfinement



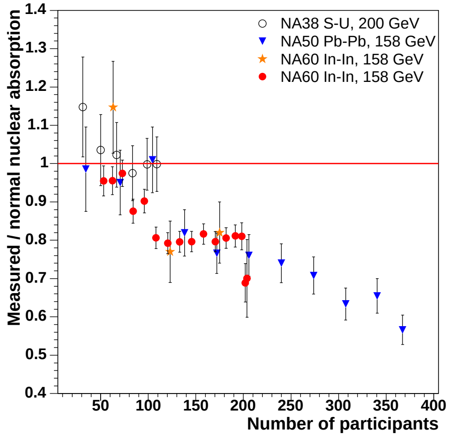
- J/ψ suppression

- J/ψ suppression
  - Observed at SPS



R.Arnaldi @ QM2005

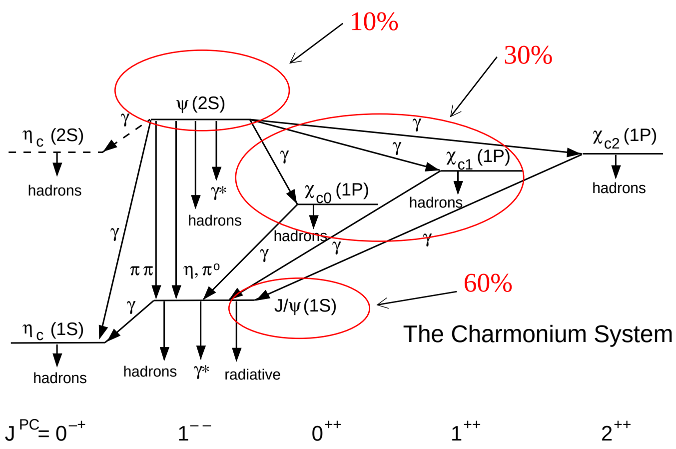
- J/ψ suppression
  - Observed at SPS



R.Arnaldi @ QM2005

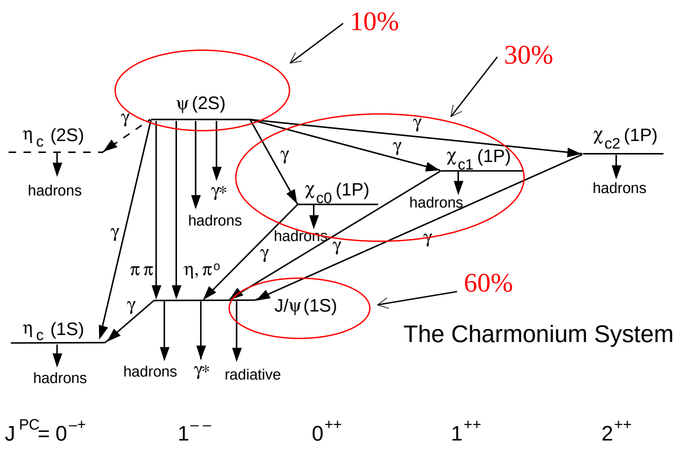
- Why the suppression ?
  - Color screening prevents formation of bound states (Matsui and Satz, Phys. Lett. B 178, 416)
  - Dynamical counterpart: Scattering with hard deconfined gluons in the plasma breaks up bound states (Kharzeev and Satz, Phys. Lett. B 334, 155)

- Around 40% of the observed J/ψ are generated by feed-down from heavier charmonia
- Same rule applies to other quarkonia



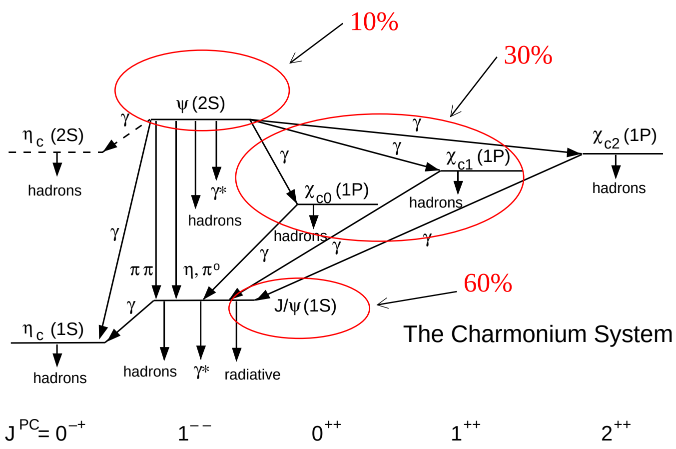
A suppression model

- Around 40% of the observed J/ψ are generated by feed-down from heavier charmonia
- Same rule applies to other quarkonia



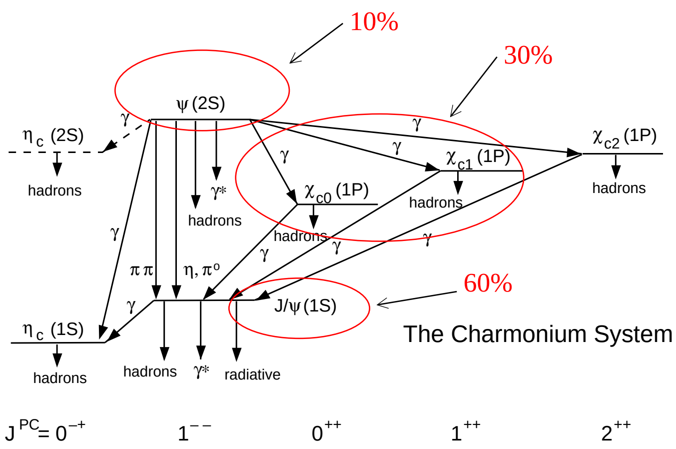
- Need for a ”sequential suppression” model.

- Around 40% of the observed J/ψ are generated by feed-down from heavier charmonia
- Same rule applies to other quarkonia



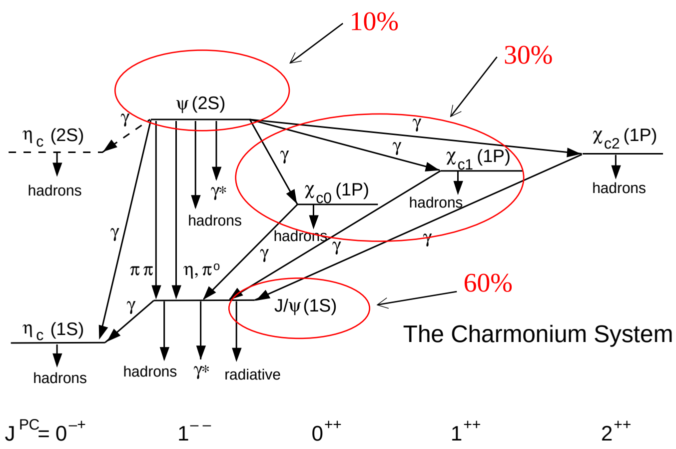
- Need for a "sequential suppression" model.
- Study of heavy mesons:

- Around 40% of the observed J/ψ are generated by feed-down from heavier charmonia
- Same rule applies to other quarkonia



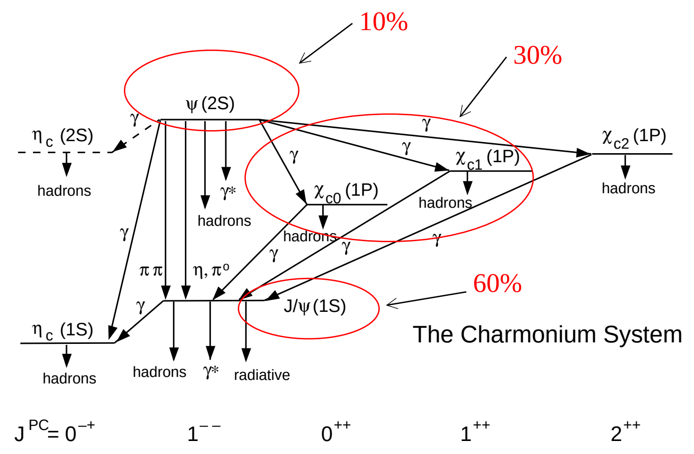
- Need for a "sequential suppression" model.
- Study of heavy mesons:
  - $c\bar{c}$ $\quad (J/\psi, \psi', \chi_c \ldots)$

- Around 40% of the observed J/ψ are generated by feed-down from heavier charmonia
- Same rule applies to other quarkonia



- Need for a ”sequential suppression” model.
- Study of heavy mesons:
  - $c\bar{c}$ $(J/\psi, \psi', \chi_c \dots)$
  - $b\bar{b}$ $(\Upsilon, \Upsilon', \chi_b \dots)$

- Around 40% of the observed J/ψ are generated by feed-down from heavier charmonia
- Same rule applies to other quarkonia



- Need for a "sequential suppression" model.
- Study of heavy mesons:
  - $c\bar{c}$ $(J/\psi, \psi', \chi_c \ldots)$
  - $b\bar{b}$ $(\Upsilon, \Upsilon', \chi_b \ldots)$
  - $b\bar{c}$, $c\bar{b}$ $(B_c , B_c', \chi_{B_c} \ldots)$

Heavy mesons in the QGP

The approach

The approach

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism
  - Schroedinger equation:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T)$$

$V(r,T) \longrightarrow$ Temperature-dependant effective potential

μ = reduced mass, ϵ = energy

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism
  - Schroedinger equation:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T)$$

$V(r,T) \longrightarrow$ Temperature-dependant effective potential

μ = reduced mass, ϵ = energy

- What for ?

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism
  - Schroedinger equation:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T)$$

$V(r,T) \longrightarrow$ Temperature-dependant effective potential

μ = reduced mass, ϵ = energy

- What for ?
  - Binding energy of the $Q\bar{Q}$ states

The approach

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism
  - Schroedinger equation:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T)$$

$V(r,T) \longrightarrow$ Temperature-dependant effective potential

μ = reduced mass, ϵ = energy

- What for ?
  - Binding energy of the $Q\bar{Q}$ states $\longrightarrow$ Dissociation temperatures

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism
  - Schroedinger equation:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T)$$

$V(r,T) \longrightarrow$ Temperature-dependant effective potential
μ = reduced mass, ϵ = energy

- What for ?
  - Binding energy of the $Q\bar{Q}$ states $\longrightarrow$ Dissociation temperatures
  - Radial wave functions

- Bound states of heavy quarks $\longrightarrow$ non-relativistic formalism
  - Schroedinger equation:

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T)$$

$V(r,T) \longrightarrow$ Temperature-dependant effective potential

μ = reduced mass, ϵ = energy

- What for ?
  - Binding energy of the $Q\bar{Q}$ states $\longrightarrow$ Dissociation temperatures
  - Radial wave functions $\longrightarrow$ Spectral functions.

Spectral functions from lattice QCD

- Lattice QCD $\longrightarrow$ Euclidean correlators (imaginary time)

- Lattice QCD $\longrightarrow$ Euclidean correlators (imaginary time)

$$G_M(\tau, T) = \langle j_M(\tau) j_M^\dagger(0) \rangle_T$$

$$j_M = \bar{q}\Gamma_M q \qquad \Gamma_M = 1, \gamma_\mu, \gamma_5, \gamma_\mu\gamma_5$$

- Lattice QCD $\longrightarrow$ Euclidean correlators (imaginary time)

$$G_M(\tau, T) = \langle j_M(\tau) j_M^\dagger(0) \rangle_T$$

$$j_M = \bar{q} \Gamma_M q \qquad \Gamma_M = 1, \gamma_\mu, \gamma_5, \gamma_\mu \gamma_5$$

- Euclidean correlators $\leftrightarrow$ Spectral functions $\sigma_M(\omega, T)$

$$G_M(\tau, T) = \int_0^\infty d\omega \sigma_M(\omega, T) K(\tau, \omega, T)$$

$$K(\tau, \omega, T) = \frac{cosh[\omega(\tau - \frac{T}{2})]}{senh(\frac{\omega}{2T})}$$

- Lattice QCD $\longrightarrow$ Euclidean correlators (imaginary time)

$$G_M(\tau, T) = \langle j_M(\tau) j_M^\dagger(0) \rangle_T$$

$$j_M = \bar{q}\Gamma_M q \qquad \Gamma_M = 1, \gamma_\mu, \gamma_5, \gamma_\mu\gamma_5$$

- Euclidean correlators $\leftrightarrow$ Spectral functions $\sigma_M(\omega, T)$

$$G_M(\tau, T) = \int_0^\infty d\omega \sigma_M(\omega, T) K(\tau, \omega, T)$$

$$K(\tau, \omega, T) = \frac{cosh[\omega(\tau - \frac{T}{2})]}{senh(\frac{\omega}{2T})}$$

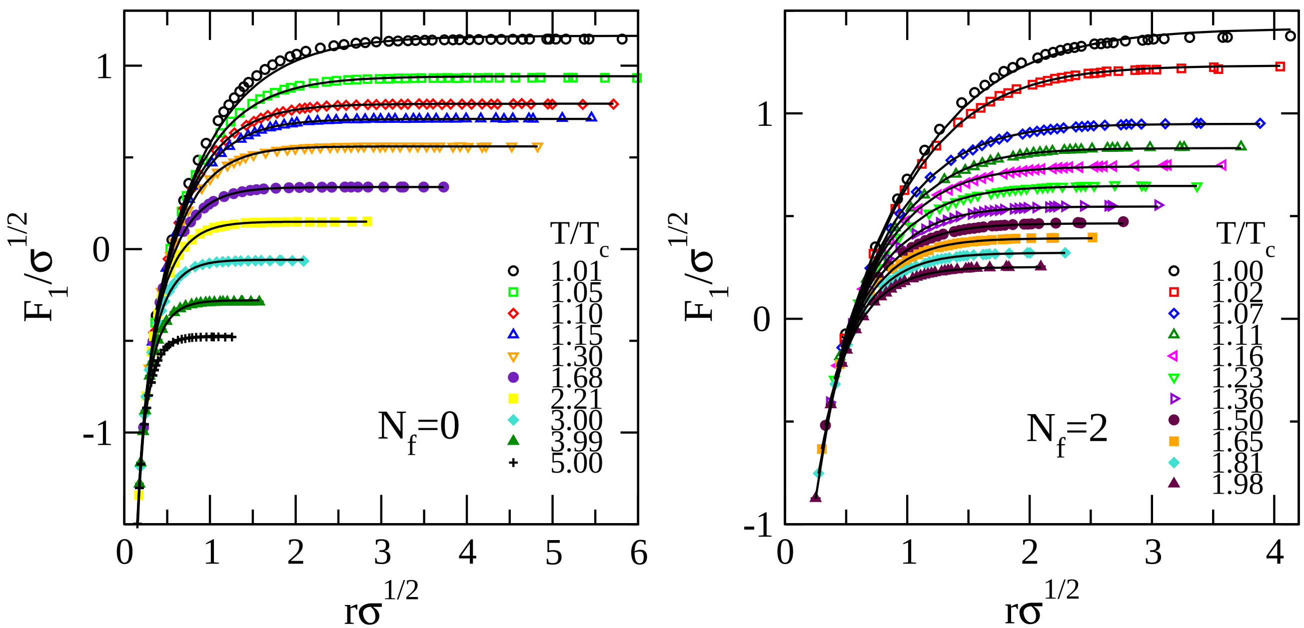
- Integral transform $\longrightarrow$ hard to extract $\sigma_M(\omega, T)$ $\longrightarrow$ MEM

- From lattice QCD:
  - $< L >_T \rightarrow F_1$ color singlet free energy

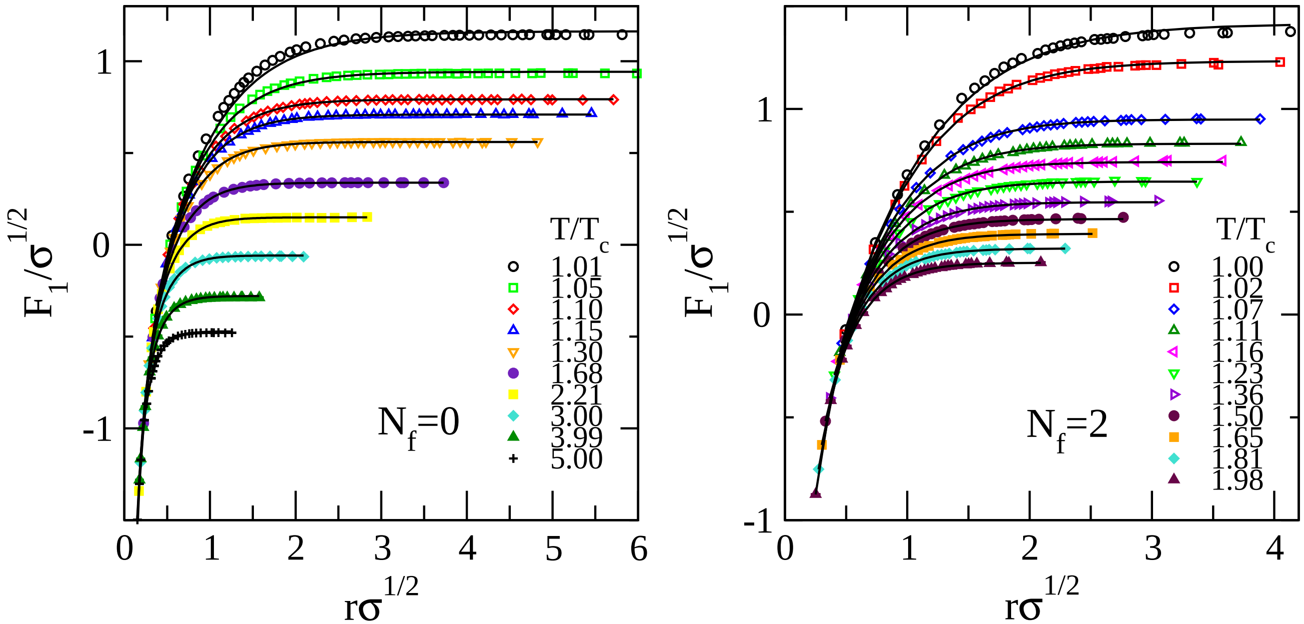
The effective potentials

- From lattice QCD:
  - $< L >_T \rightarrow F_1$ color singlet free energy
  - Fit on lattice data $\longrightarrow$ functional dependence $F_1(T)$
    (W.M. Alberico et al., Phys. Rev. D, 72, 114011)

- From lattice QCD:
  - $< L >_T \to F_1$ color singlet free energy
  - Fit on lattice data $\to$ functional dependence $F_1(T)$
    (W.M. Alberico et al., Phys. Rev. D, 72, 114011)



- From lattice QCD:
  - $< L >_T \rightarrow F_1$ color singlet free energy
  - Fit on lattice data $\rightarrow$ functional dependence $F_1(T)$ (W.M. Alberico et al., Phys. Rev. D, 72, 114011)



  - $F_1(T) \rightarrow U_1 = -T^2 \frac{\partial}{\partial T}(\frac{F_1}{T})$ singlet internal energy

- Possibilities: $F_1, U_1 \ldots$

- Possibilities: $F_1, U_1 \ldots$

- Hydrodinamical / Thermodynamical considerations $\longrightarrow$ isolating effective $Q\bar{Q}$ potential from the plasma contribution

  (C.Y.Wong, Phys. Rev. C, 72, 034906)

Which potential?

- Possibilities: $F_1, U_1 \ldots$
- Hydrodinamical / Thermodynamical considerations $\longrightarrow$ isolating effective $Q\bar{Q}$ potential from the plasma contribution

  (C.Y.Wong, Phys. Rev. C, 72, 034906)

$$U_{Q\bar{Q}}(r,T) = f_F(T)F_1(r,T) + f_U(T)U_1(r,T)$$

$$f_F = \frac{3}{3+a(T)}$$

$$f_U = \frac{a(T)}{3+a(T)}$$

$$a(T) = \frac{3p}{\epsilon}$$

- Possibilities: $F_1, U_1 \ldots$
- Hydrodinamical / Thermodynamical considerations $\longrightarrow$ isolating effective $Q\bar{Q}$ potential from the plasma contribution

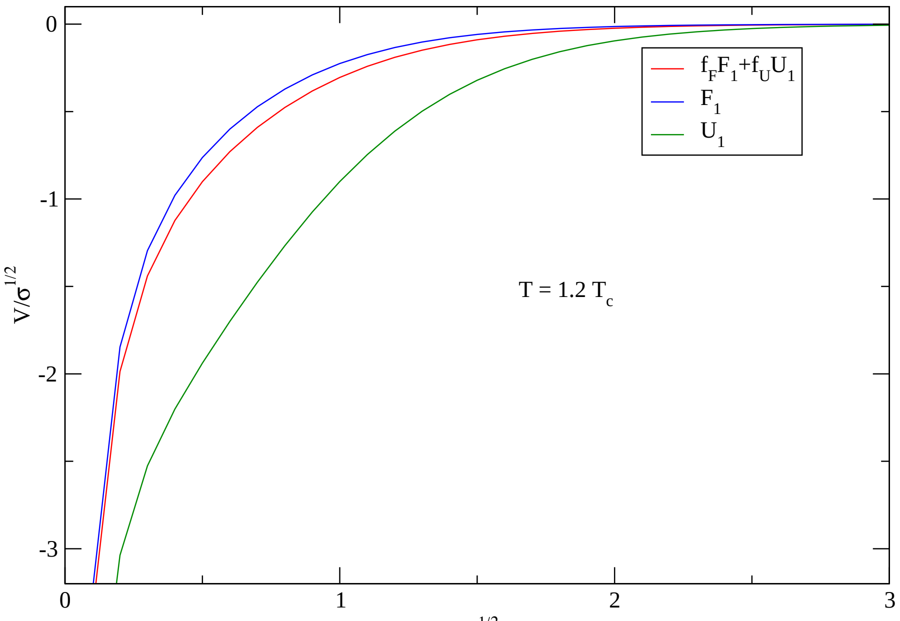
  (C.Y.Wong, Phys. Rev. C, 72, 034906)

$$U_{Q\bar{Q}}(r,T) = f_F(T)F_1(r,T) + f_U(T)U_1(r,T)$$

$$f_F = \frac{3}{3+a(T)}$$

$$f_U = \frac{a(T)}{3+a(T)}$$

$$a(T) = \frac{3p}{\epsilon}$$



Quark masses

- Quark charm: m_c = 1.4 - 1.6 GeV
- Quark bottom: m_b = 4.3 - 4.7 GeV

Quark masses

- Quark charm: m_c = 1.4 - 1.6 GeV
- Quark bottom: m_b = 4.3 - 4.7 GeV
- Effective mass : $\tilde{m}_Q(T) = m_Q + \frac{1}{2}U_{Q\bar{Q}}(r \rightarrow \infty, T)$

Quark masses

- Quark charm: m_c = 1.4 - 1.6 GeV
- Quark bottom: m_b = 4.3 - 4.7 GeV
- Effective mass : $\tilde{m}_Q(T)$ = $m_Q + \frac{1}{2}U_{Q\bar{Q}}(r \to \infty, T)$
  - Interpreted as 'thermal' mass

Quark masses

- Quark charm: m_c = 1.4 - 1.6 GeV
- Quark bottom: m_b = 4.3 - 4.7 GeV
- Effective mass : $\tilde{m}_Q(T)$ = $m_Q + \frac{1}{2}U_{Q\bar{Q}}(r \to \infty, T)$
  - Interpreted as 'thermal' mass
  - Improves binding of the states.

- Quark charm: m_c = 1.4 - 1.6 GeV
- Quark bottom: m_b = 4.3 - 4.7 GeV
- Effective mass : $\tilde{m}_Q(T)$ = $m_Q + \frac{1}{2}U_{Q\bar{Q}}(r \to \infty, T)$
  - Interpreted as 'thermal' mass
  - Improves binding of the states.
  - Continuum threshold: $s_0 = m_{Q_1} + m_{Q_2} + U_{Q\bar{Q}}(r \to \infty, T) = \tilde{m}_{Q_1}(T) + \tilde{m}_{Q_2}(T)$
- Does the model strongly depend on the chosen values for the quark masses ?

Results

- States $c\bar{c}$, $b\bar{b}$, $b\bar{c}$ ($c\bar{b}$)

The analyzed states

- States $c\bar{c}$, $b\bar{b}$, $b\bar{c}$ ($c\bar{b}$)
- S Wave (L=0)

- States $c\bar{c}$, $b\bar{b}$, $b\bar{c}$ ($c\bar{b}$)
- S Wave (L=0)
  - Fundamental bound states
  - Excited bound states
  - Scattering states

- States $c\bar{c}$, $b\bar{b}$, $b\bar{c}$ ($c\bar{b}$)
- S Wave (L=0)
  - Fundamental bound states
  - Excited bound states
  - Scattering states
- P Wave (L=1)

The analyzed states

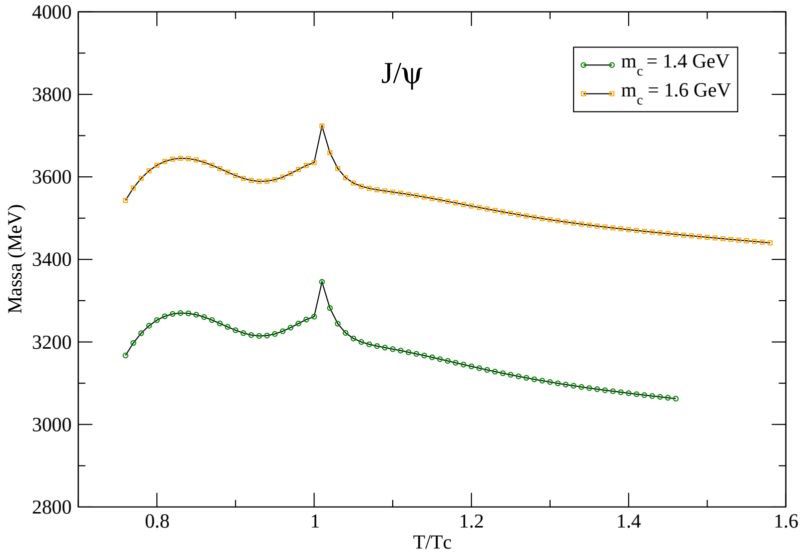
- States $c\bar{c}$, $b\bar{b}$, $b\bar{c}$ ($c\bar{b}$)
- S Wave (L=0)
  - Fundamental bound states
  - Excited bound states
  - Scattering states
- P Wave (L=1)
  - Fundamental bound states
  - Scattering states

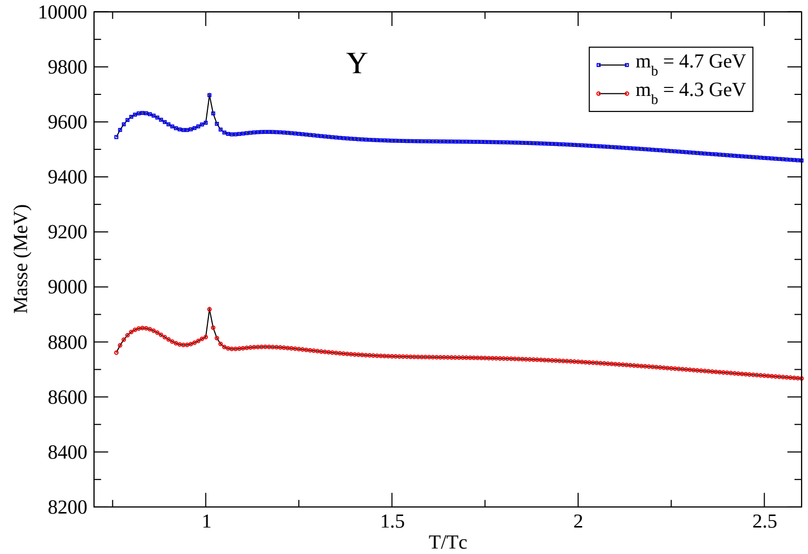
The analyzed states

- States $c\bar{c}$, $b\bar{b}$, $b\bar{c}$ ($c\bar{b}$)
- S Wave (L=0)
  - Fundamental bound states
  - Excited bound states
  - Scattering states
- P Wave (L=1)
  - Fundamental bound states
  - Scattering states
- Lattice data for F_1 obtained using $N_f = 2$

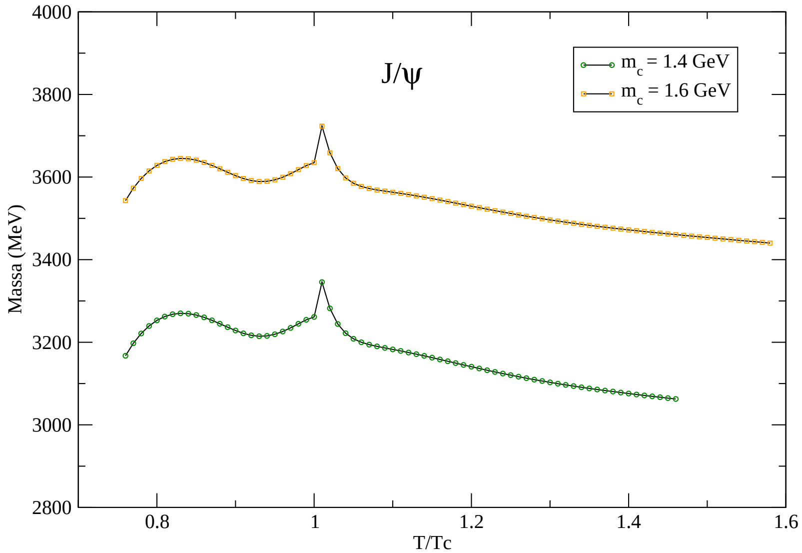
  (F. Karsch et al., Phys. Lett. B 478, 447) (2000)

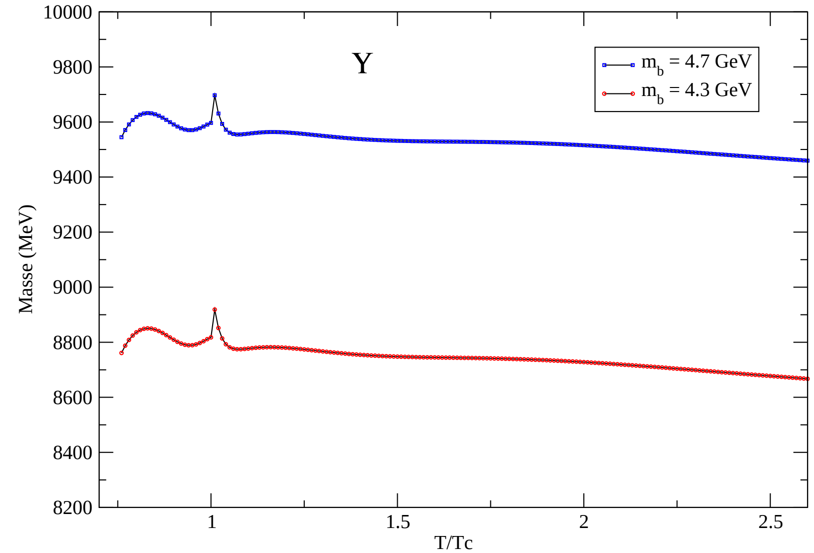
Masses $M(T) = s_0(T) + \epsilon(T)$

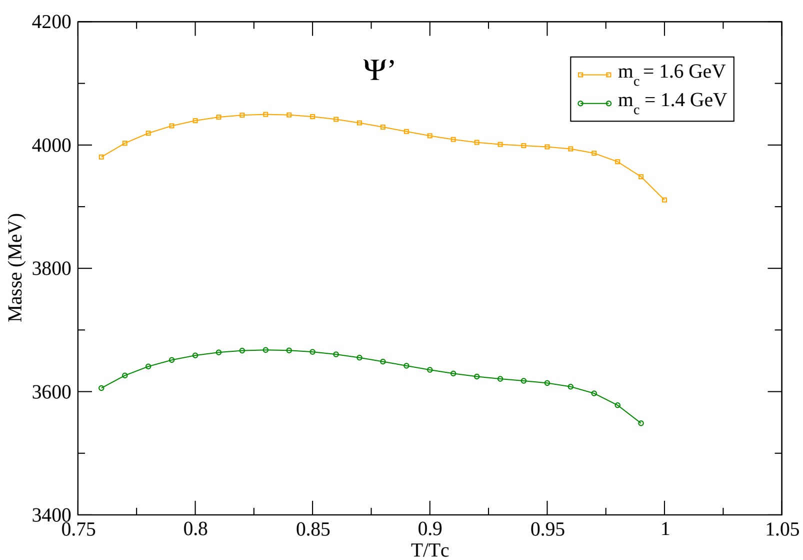

J/ψ
m_c = 1.4 GeV
m_c = 1.6 GeV
Massa (MeV)
T/Tc
4000
3800
3600
3400
3200
3000
2800
0.8
1
1.2
1.4
1.6

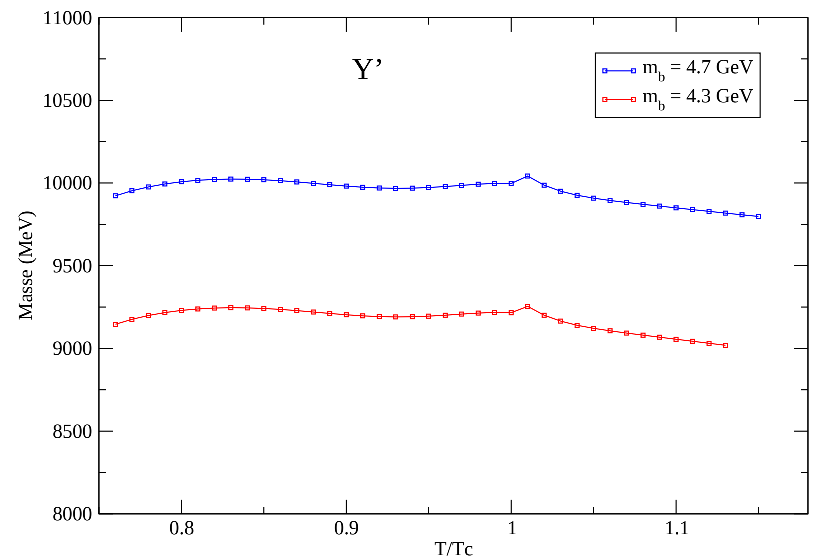

Υ
m_b = 4.7 GeV
m_b = 4.3 GeV
Masse (MeV)
T/Tc
10000
9800
9600
9400
9200
9000
8800
8600
8400
8200
1
1.5
2
2.5

Masses $M(T) = s_0(T) + \epsilon(T)$









Dissociation temperatures (T/T_c)

$c\bar{c}$	m_c=1.4 GeV	m_c=1.6 GeV	$b\bar{b}$	m_b=4.3 GeV	m_b=4.7 GeV
$J/\psi, \eta_c$	1.45	1.57	Υ, η_b	3.9	4.4
χ_c	0.99	1.00	χ_b	1.14	1.16
ψ'	0.98	1.00	Υ'	1.14	1.15

Dissociation temperatures (T/T_c)

$c\bar{c}$	m_c=1.4 GeV	m_c=1.6 GeV	$b\bar{b}$	m_b=4.3 GeV	m_b=4.7 GeV
$J/\psi, \eta_c$	1.45	1.57	Υ, η_b	3.9	4.4
χ_c	0.99	1.00	χ_b	1.14	1.16
ψ'	0.98	1.00	Υ'	1.14	1.15

- Dissociation temperatures for charmonium in good agreement with lattice QCD

Dissociation temperatures (T/T_c)

$c\bar{c}$	m_c=1.4 GeV	m_c=1.6 GeV	$b\bar{b}$	m_b=4.3 GeV	m_b=4.7 GeV
$J/\psi, \eta_c$	1.45	1.57	Υ, η_b	3.9	4.4
χ_c	0.99	1.00	χ_b	1.14	1.16
ψ'	0.98	1.00	Υ'	1.14	1.15

- Dissociation temperatures for charmonium in good agreement with lattice QCD
- Mass variation $\longrightarrow$ Difficult comparison with lattice QCD

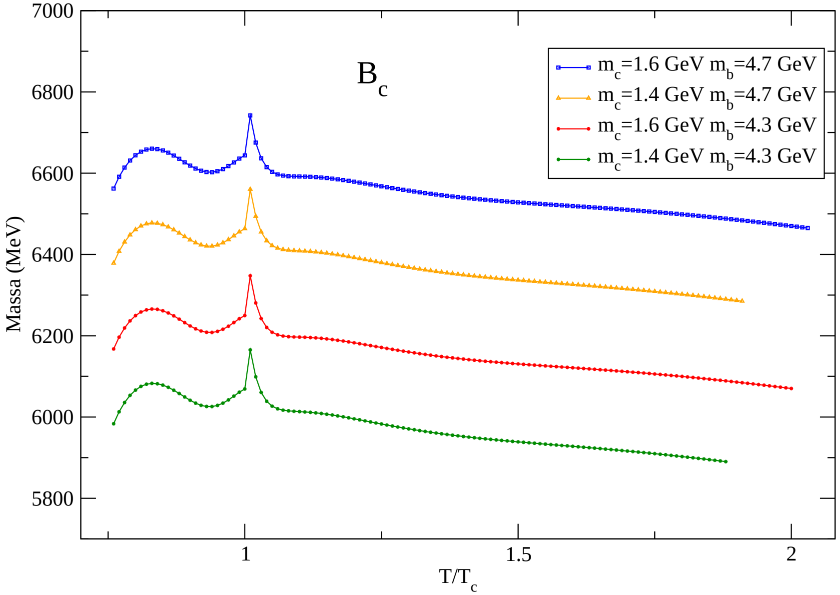
Dissociation temperatures (T/T_c)

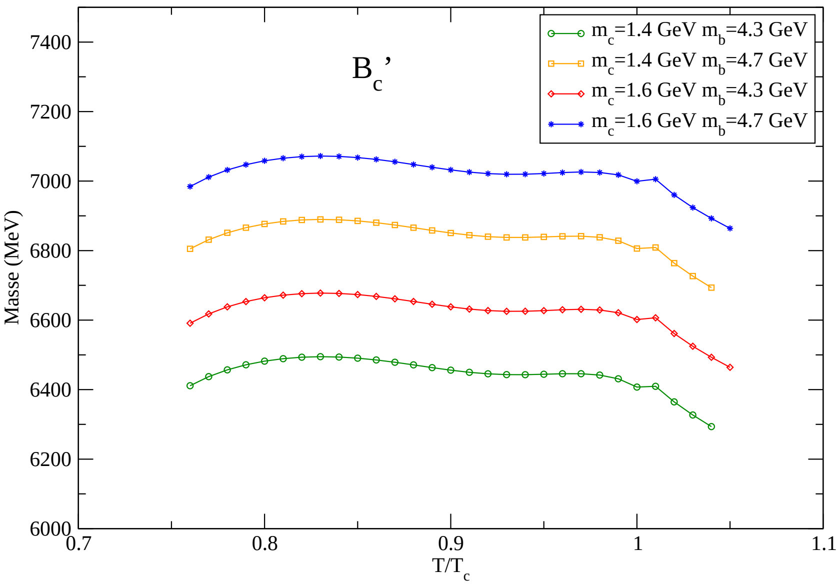
$c\bar{c}$	m_c=1.4 GeV	m_c=1.6 GeV	$b\bar{b}$	m_b=4.3 GeV	m_b=4.7 GeV
$J/\psi, \eta_c$	1.45	1.57	Υ, η_b	3.9	4.4
χ_c	0.99	1.00	χ_b	1.14	1.16
ψ'	0.98	1.00	Υ'	1.14	1.15

- Dissociation temperatures for charmonium in good agreement with lattice QCD
- Mass variation $\longrightarrow$ Difficult comparison with lattice QCD
- Dissociation temperatures do not vary significantly with different quark masses.

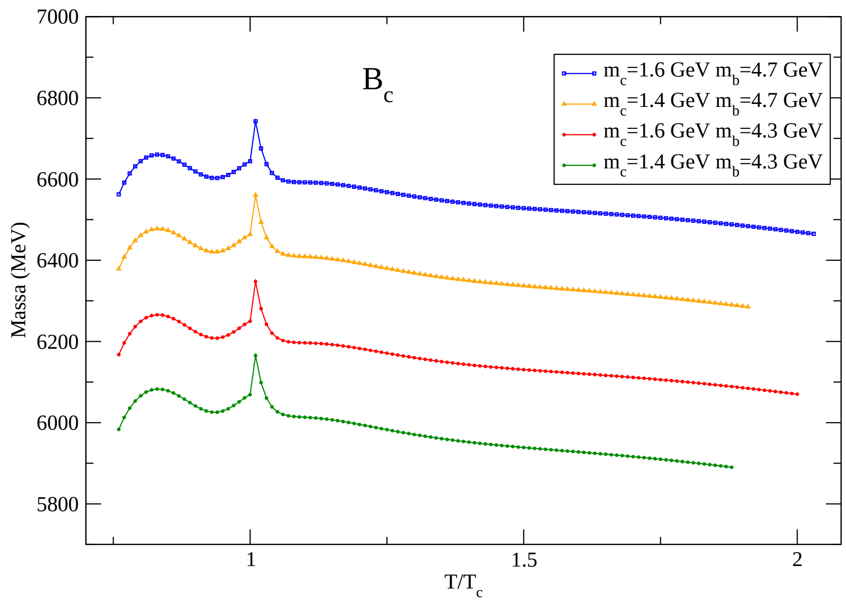
More masses: B_c

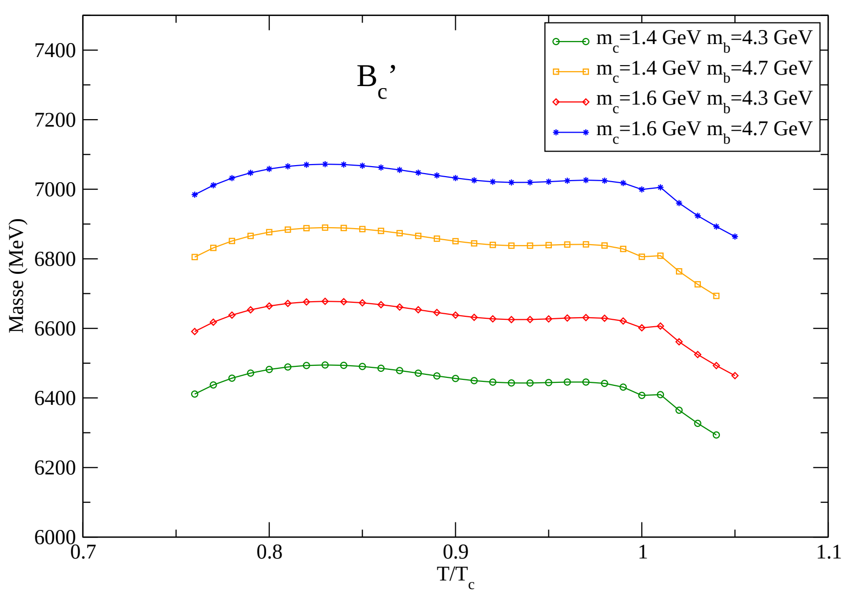
More masses: B_c





More masses: B_c

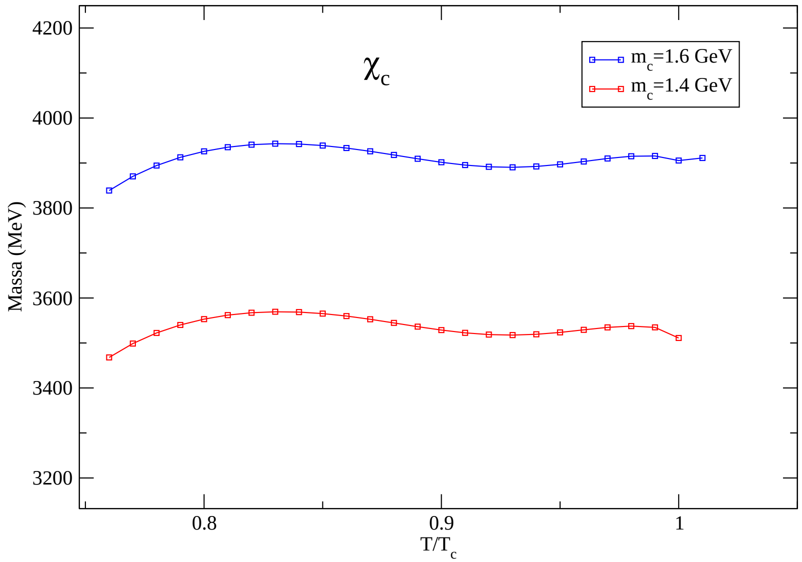




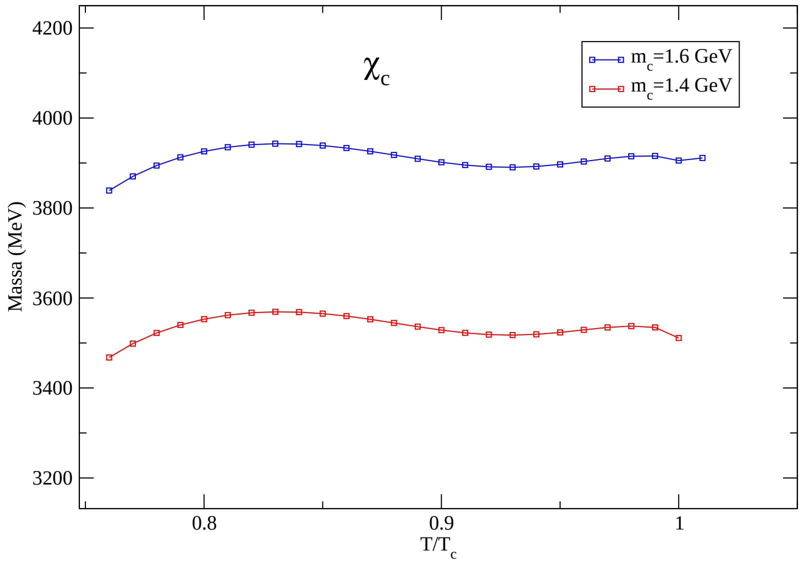
Dissociation temperatures (T/T_c)

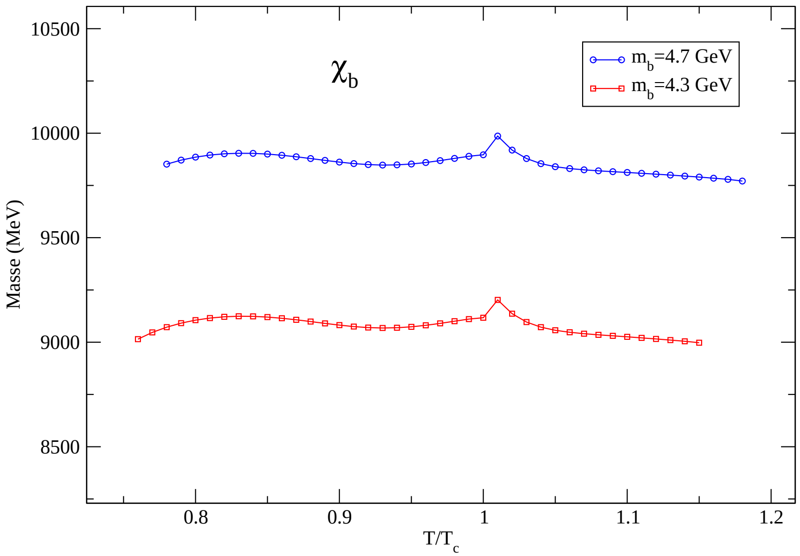
$c\bar{b}$ $b\bar{c}$	m_c=1.4 GeV m_b=4.3 GeV	m_c=1.4 GeV m_b=4.7 GeV	m_c=1.6 GeV m_b=4.3 GeV	m_c=1.6 GeV m_b=4.7 GeV
B_c	1.87	1.90	1.99	2.02
χ_{B_c}	1.05	1.05	1.06	1.06
B_c'	1.03	1.04	1.04	1.05

Even more masses: P wave states

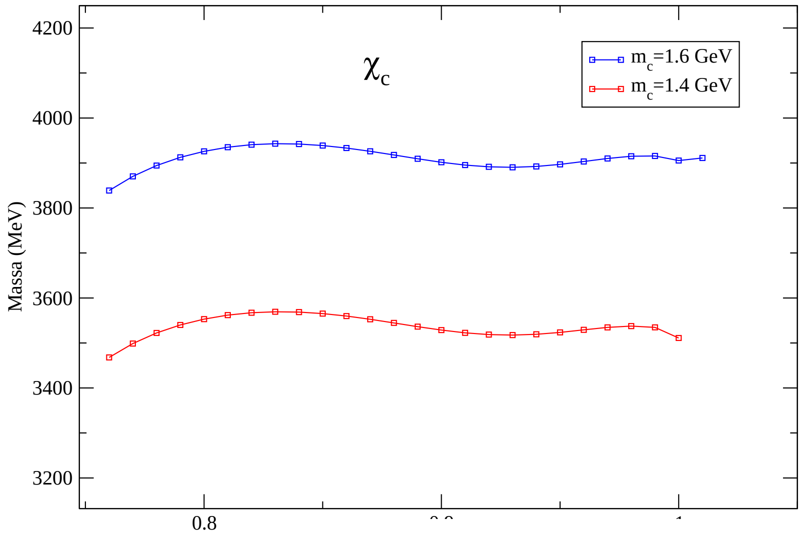


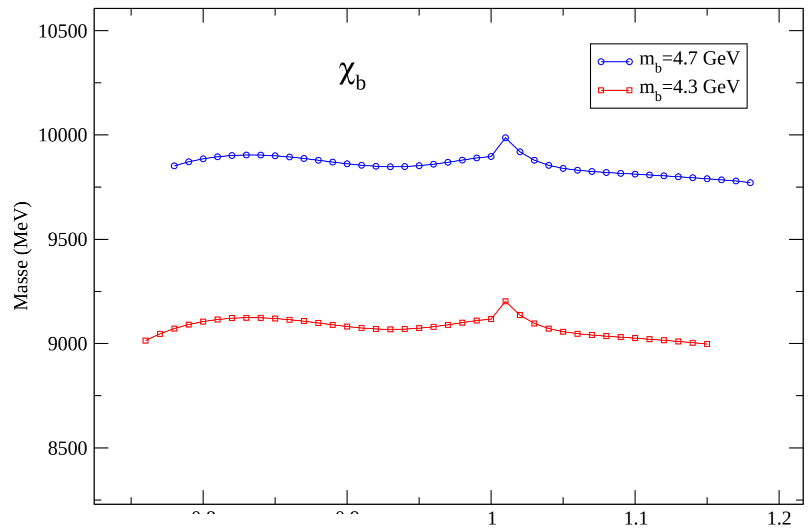
Even more masses: P wave states

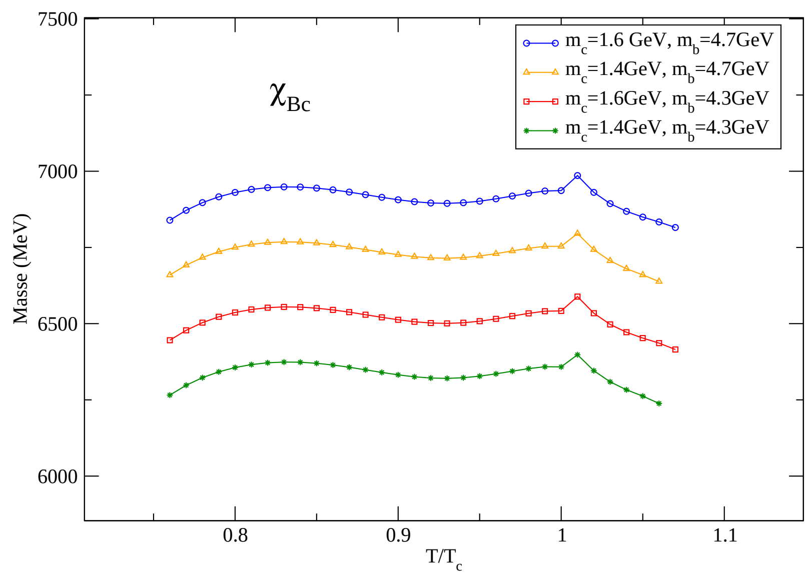




Even more masses: P wave states







Spectral functions

$$\sigma_M(\omega, T) = \frac{1}{\pi} Im G_M(\omega) = \sum_n |\langle 0 \mid j_M \mid n \rangle|^2 \delta(\omega - E_n) =$$

$$\sigma_M(\omega,T)=\frac{1}{\pi}ImG_M(\omega)=\sum_n|\langle 0\mid j_M\mid n\rangle|^2\delta(\omega-E_n)=$$

$$=\sum_n F^2_{M,n}\delta(\omega-E_n)+\theta(\omega-s_0)F^2_{M,\epsilon}$$

$$\sigma_M(\omega,T)=\frac{1}{\pi}ImG_M(\omega)=\sum_n |\langle 0\mid j_M\mid n\rangle|^2\delta(\omega-E_n)=$$

$$=\sum_n F^2_{M,n}\delta(\omega-E_n)+\theta(\omega-s_0)F^2_{M,\epsilon}$$

- Non-relativistic QCD:
  $F^2_{M,n}=|\langle 0\mid j_M\mid n\rangle|^2=f(|R(0)|^2,|R'(0)|^2)$

  $R(0)\rightarrow$ Value of the radial wave function $R(r)$ in the origin

$$\sigma_M(\omega,T) = \frac{1}{\pi} Im G_M(\omega) = \sum_n |\langle 0 \mid j_M \mid n\rangle|^2 \delta(\omega - E_n) =$$

$$= \sum_n F^2_{M,n}\delta(\omega - E_n) + \theta(\omega - s_0) F^2_{M,\epsilon}$$

- Non-relativistic QCD:
  $F^2_{M,n} = |\langle 0 \mid j_M \mid n\rangle|^2 = f(|R(0)|^2, |R'(0)|^2)$

  $R(0) \rightarrow$ Value of the radial wave function $R(r)$ in the origin

- For example..

$$\sigma_M(\omega,T)=\frac{1}{\pi}ImG_M(\omega)=\sum_n|\langle 0\mid j_M\mid n\rangle|^2\delta(\omega-E_n)=$$

$$=\sum_n F^2_{M,n}\delta(\omega-E_n)+\theta(\omega-s_0)F^2_{M,\epsilon}$$

- Non-relativistic QCD:
  $F^2_{M,n}=|\langle 0\mid j_M\mid n\rangle|^2=f(|R(0)|^2,|R'(0)|^2)$

  $R(0)\longrightarrow$ Value of the radial wave function $R(r)$ in the origin

- For example.. (G.T.Bodwin et al., Phys. Rev. D 51, 1125)
  - Vector (S wave): $F^2_V=\frac{3N_c}{2\pi}|R(0)|^2$;

$$\sigma_M(\omega, T) = \frac{1}{\pi} Im G_M(\omega) = \sum_n |\langle 0 \mid j_M \mid n\rangle|^2 \delta(\omega - E_n) =$$

$$= \sum_n F^2_{M,n} \delta(\omega - E_n) + \theta(\omega - s_0) F^2_{M,\epsilon}$$

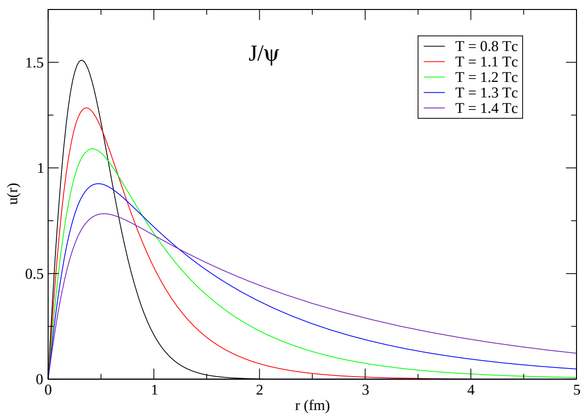
- Non-relativistic QCD:
  $F^2_{M,n} = |\langle 0 \mid j_M \mid n\rangle|^2 = f(|R(0)|^2, |R'(0)|^2)$

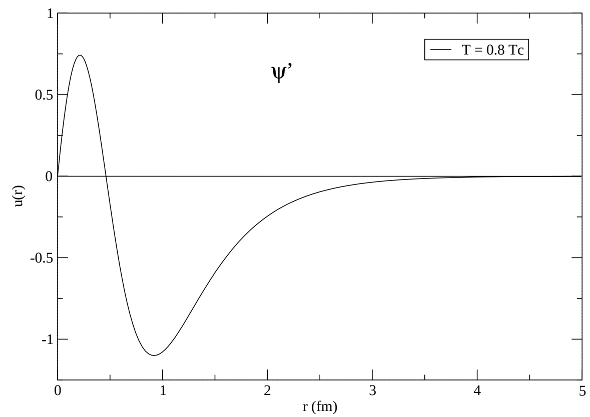
  $R(0) \longrightarrow$ Value of the radial wave function $R(r)$ in the origin

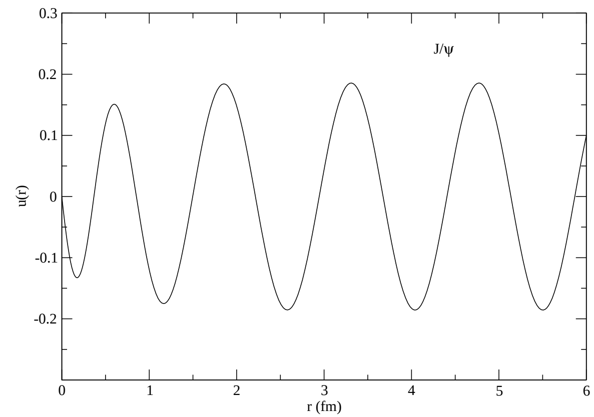
- For example.. (G.T.Bodwin et al., Phys. Rev. D 51, 1125)
  - Vector (S wave): $F^2_V = \frac{3N_c}{2\pi} |R(0)|^2$;
  - Scalar (P wave): $F^2_S = \frac{9N_c}{2\pi m^2} |R'(0)|^2$;

- By integrating Schroedinger's equation $\longrightarrow$ Radial wave functions

- By integrating Schroedinger's equation $\longrightarrow$ Radial wave functions

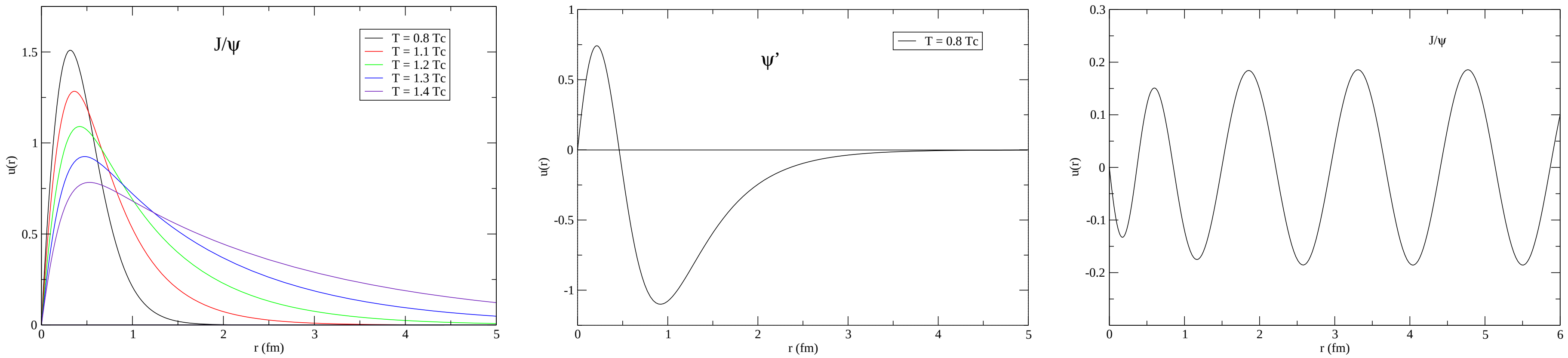






Wave functions

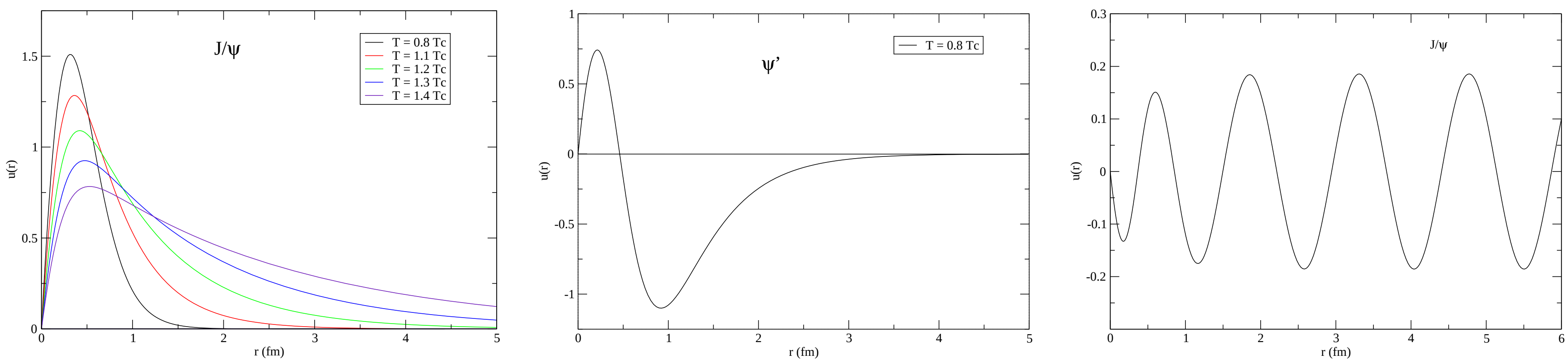
- By integrating Schroedinger's equation ⟶ Radial wave functions



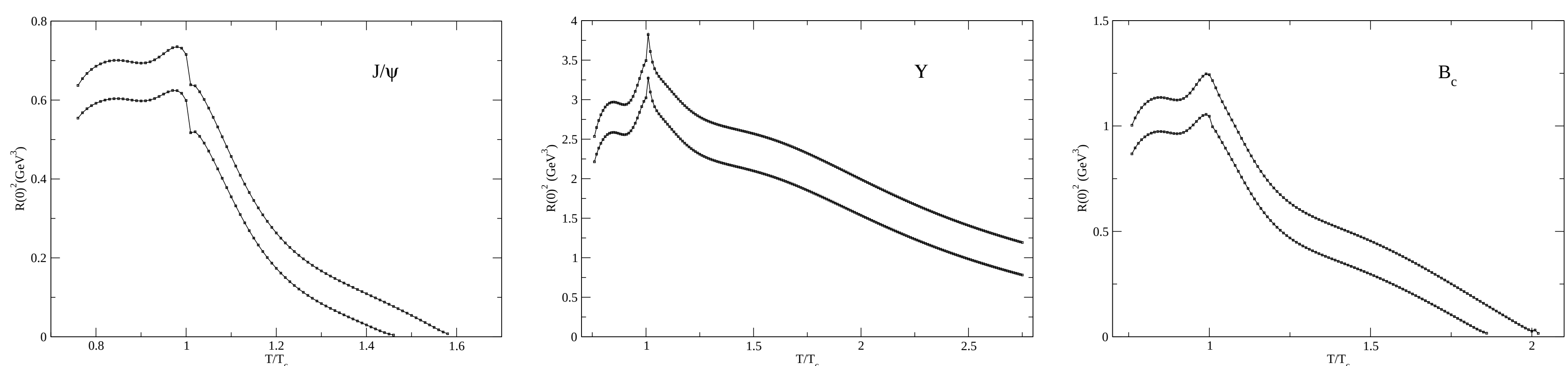
- From the radial wave functions R(r) ⟶ R(0), R'(0)..

Wave functions

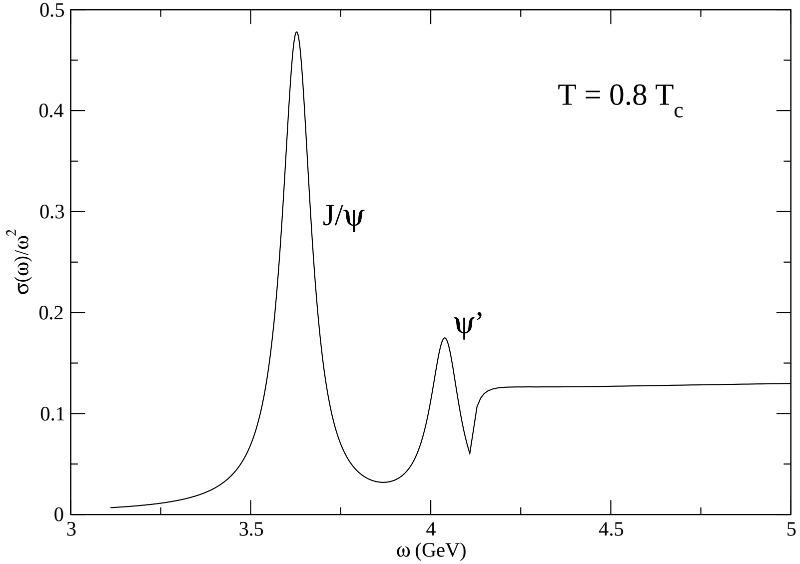
- By integrating Schroedinger's equation ⟶ Radial wave functions

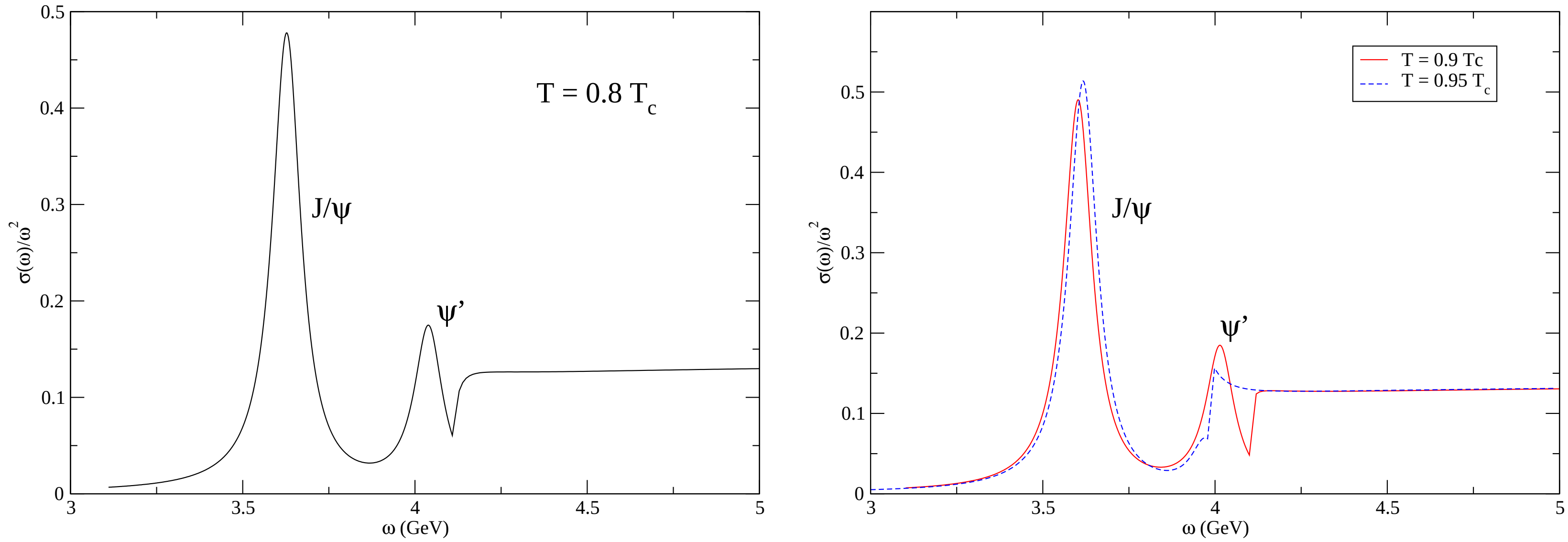


- From the radial wave functions R(r) ⟶ R(0), R'(0)

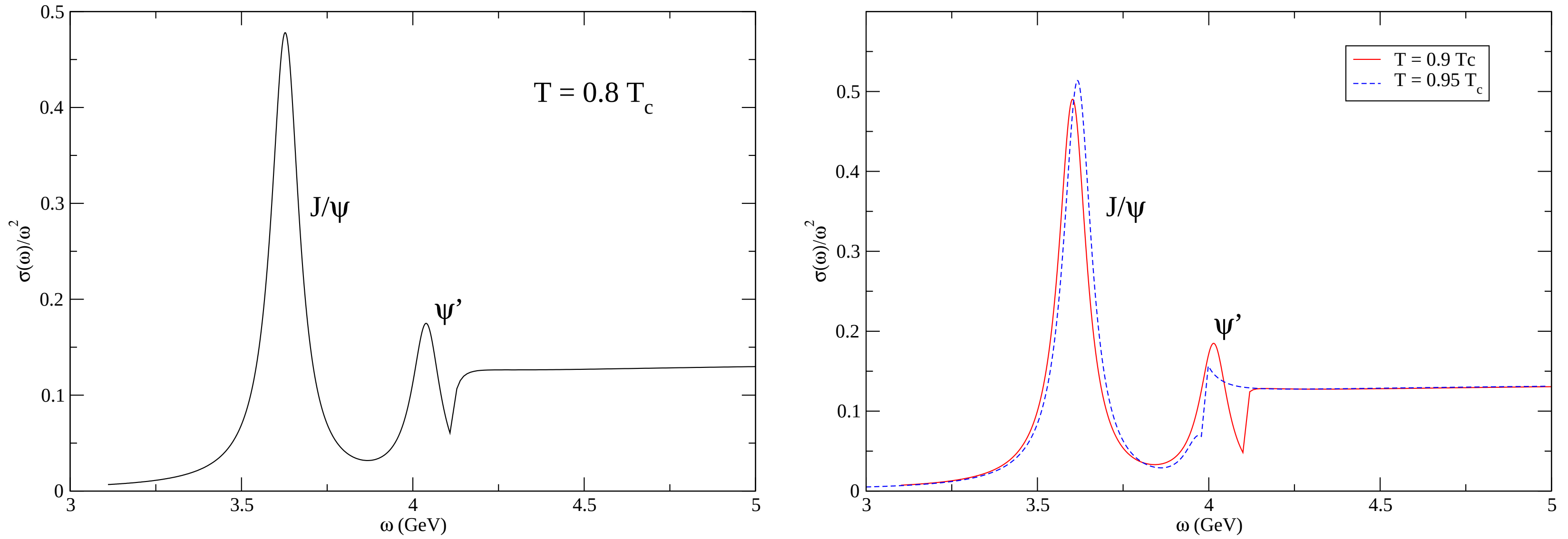


Spectral Functions: J/ψ

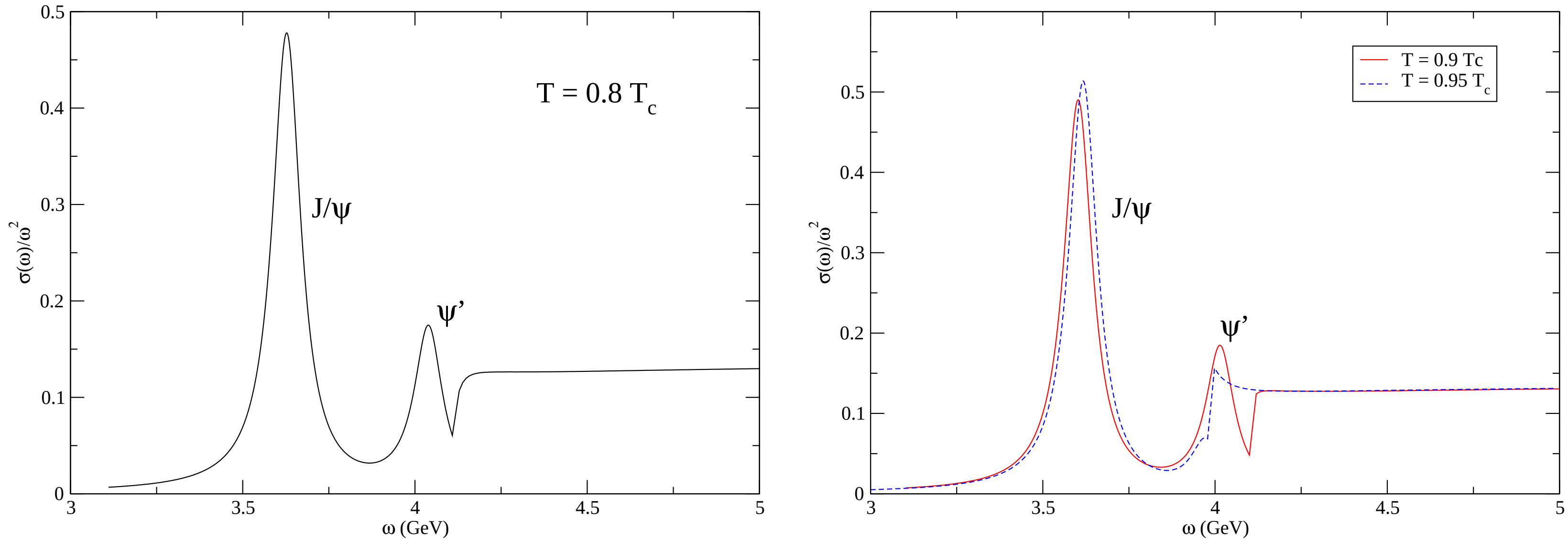

T = 0.8 T_c
J/ψ
ψ'
σ(ω)/ω²
ω (GeV)
0
0.1
0.2
0.3
0.4
0.5
3
3.5
4
4.5
5


T = 0.8 T_c
J/ψ
ψ'
σ(ω)/ω^2
ω (GeV)
T = 0.9 Tc
T = 0.95 T_c
J/ψ
ψ'
σ(ω)/ω^2
ω (GeV)

Spectral Functions: J/ψ

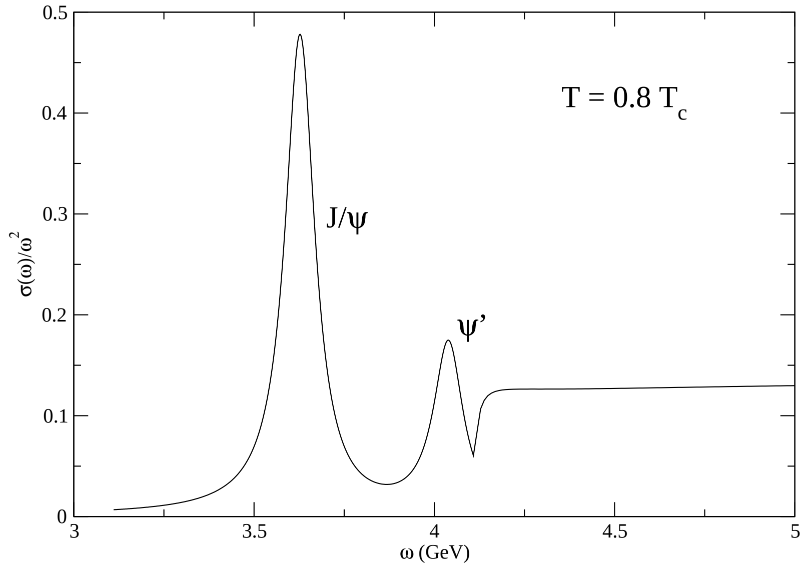


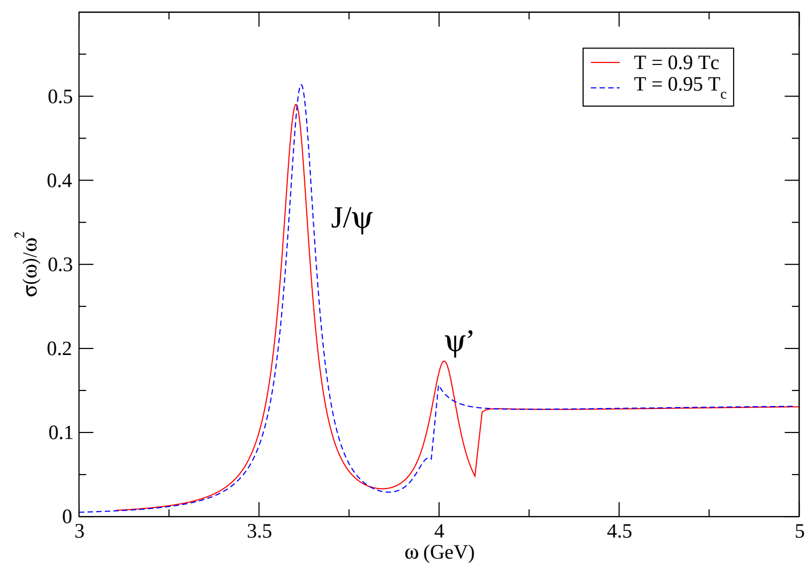
- Broadening of the bound state peaks added 'ad hoc' ($\Gamma \approx 100 MeV$)



- Broadening of the bound state peaks added 'ad hoc' ($\Gamma \approx 100 MeV$)
- Kinematic corrections to the scattering contribution $\longrightarrow$ reproduce correct $\propto \omega^2$ asymptotic behavour of perturbative QCD

Spectral Functions: J/ψ

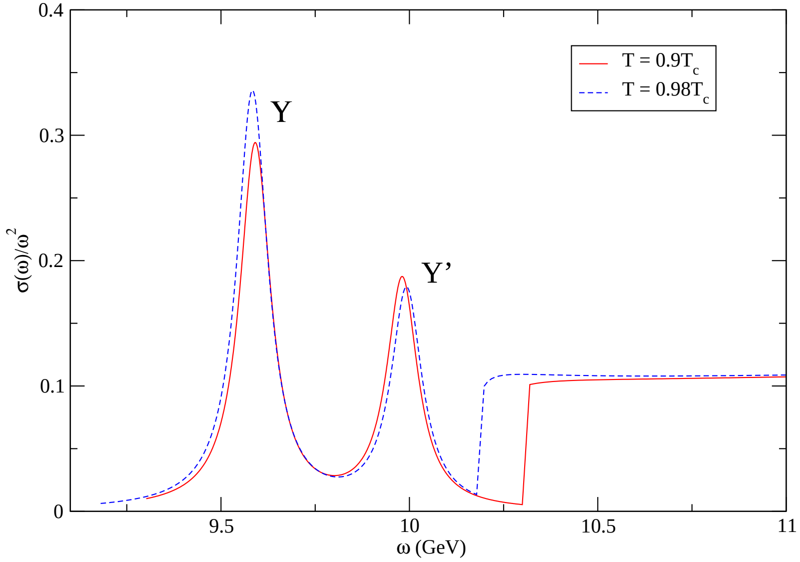


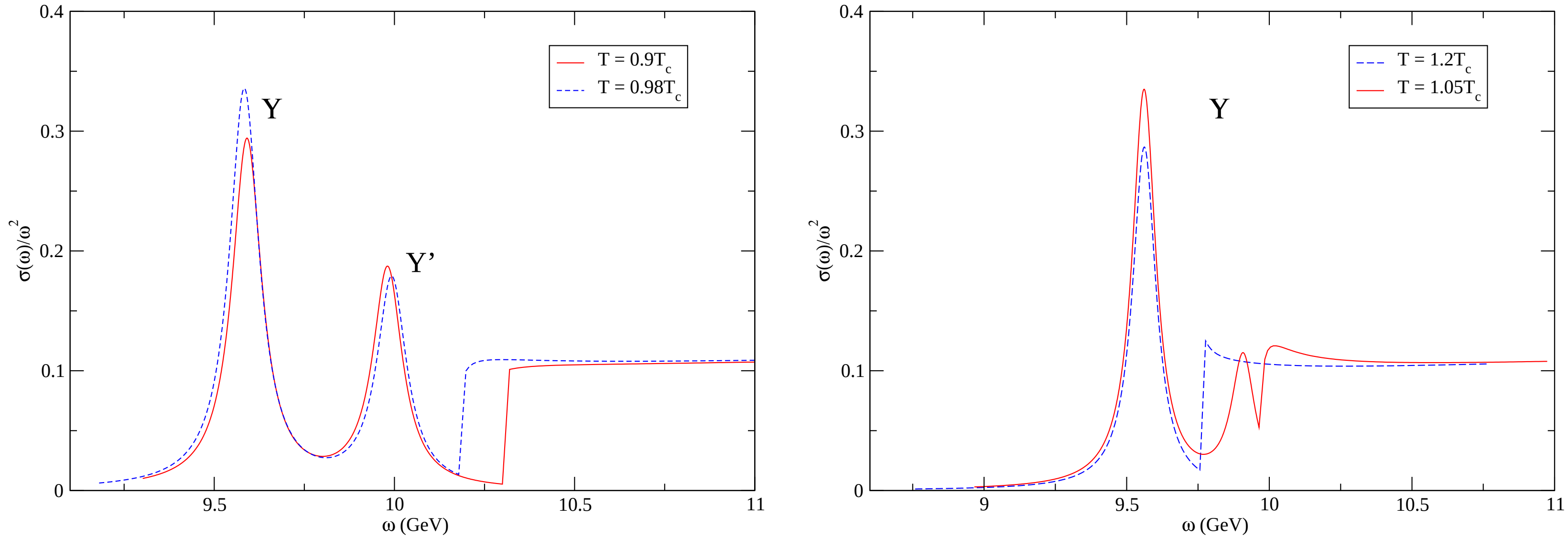


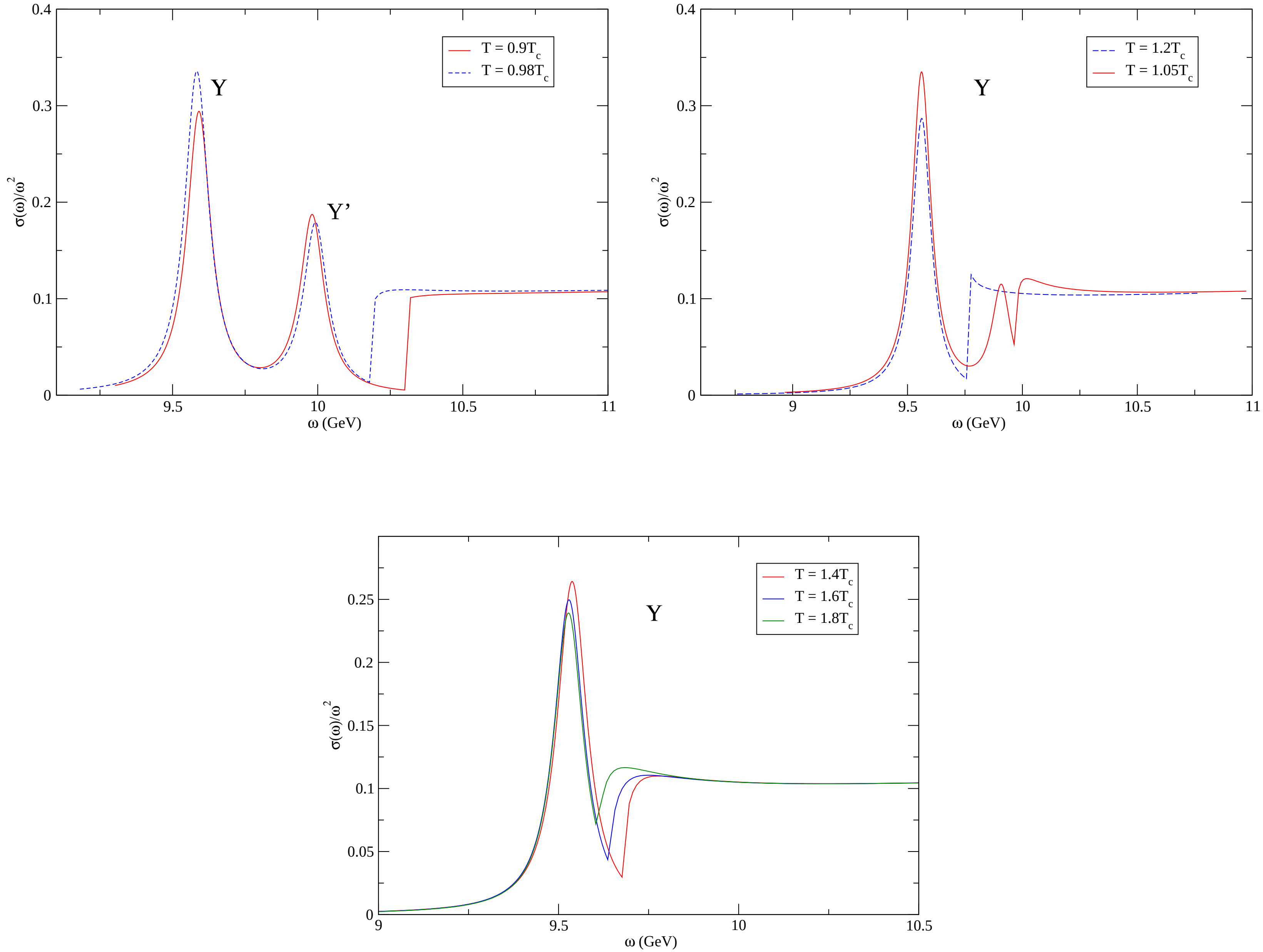
- Broadening of the bound state peaks added 'ad hoc' ($\Gamma \approx 100MeV$)
- Kinematic corrections to the scattering contribution $\longrightarrow$ reproduce correct $\propto \omega^2$ asymptotic behavour of perturbative QCD
- A direct comparison with lattice QCD results is very hard to realize.

Spectral functions: Υ

Spectral functions: Υ

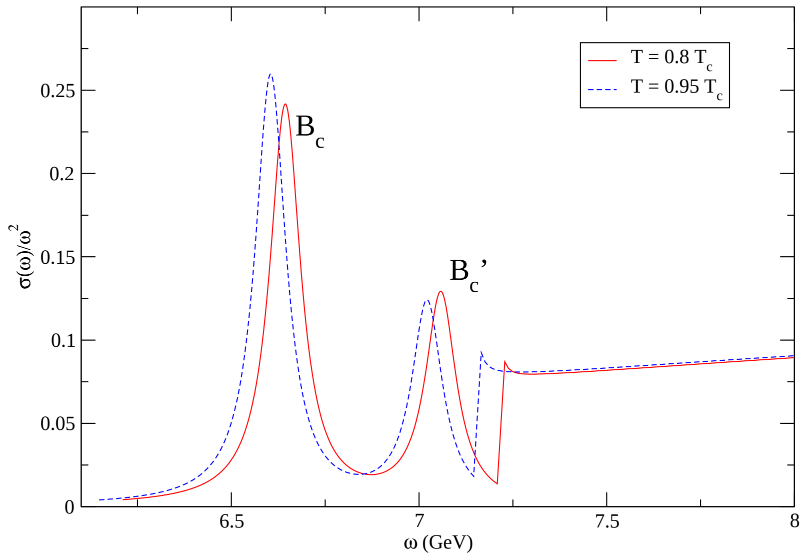


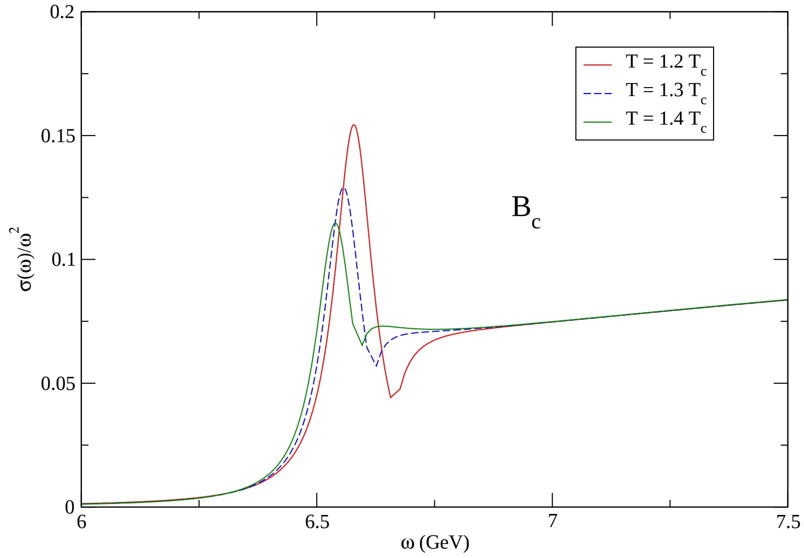

0.4
0.3
0.2
0.1
0
σ(ω)/ω²
Y
Y'
T = 0.9T_c
T = 0.98T_c
9.5
10
10.5
11
ω (GeV)
0.4
0.3
0.2
0.1
0
σ(ω)/ω²
Y
T = 1.2T_c
T = 1.05T_c
9
9.5
10
10.5
11
ω (GeV)

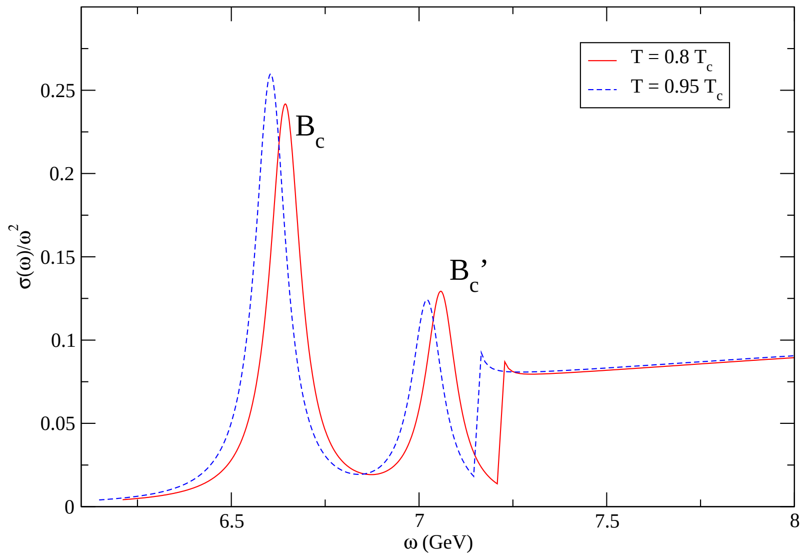


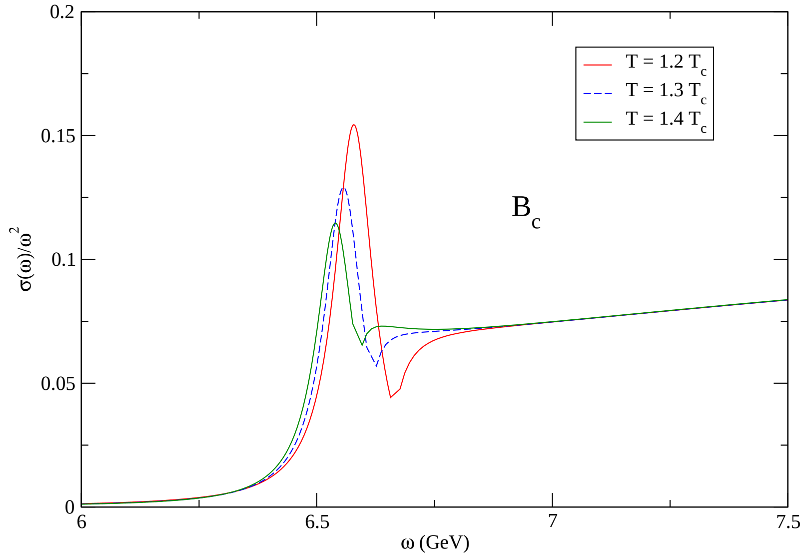
T = 0.9T_c
T = 0.98T_c
Y
Y'
σ(ω)/ω^2
ω (GeV)
T = 1.2T_c
T = 1.05T_c
Y
σ(ω)/ω^2
ω (GeV)
T = 1.4T_c
T = 1.6T_c
T = 1.8T_c
Y
σ(ω)/ω^2
ω (GeV)

Spectral functions: B_c

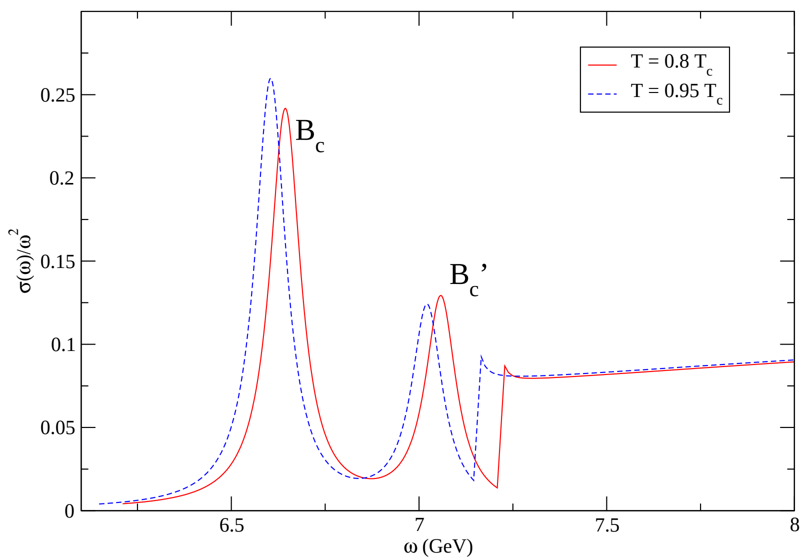


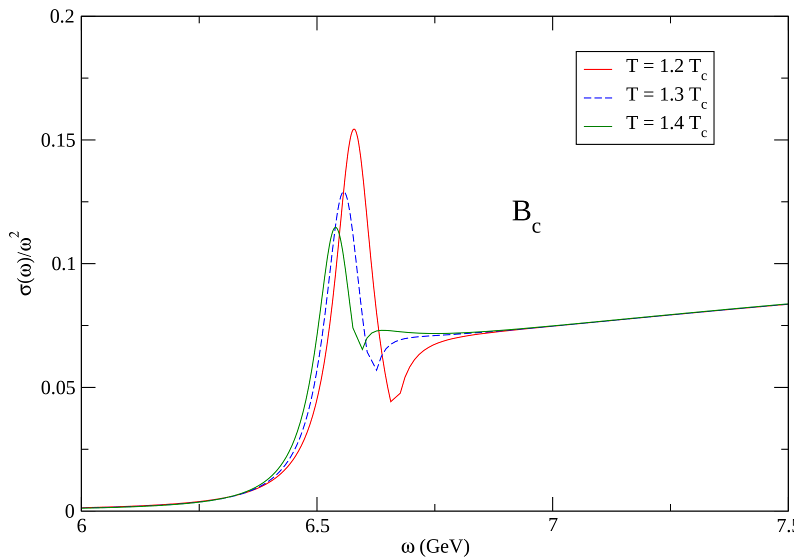






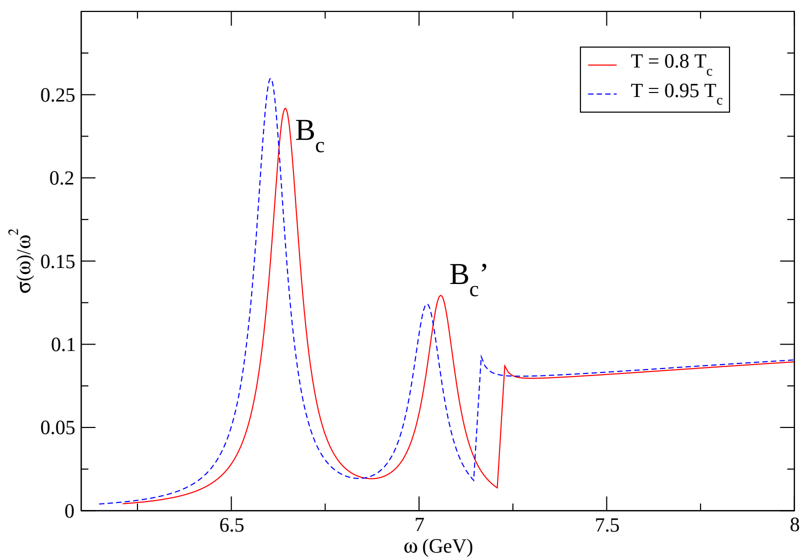
- Fundamental state survives beyond T_c
- Radial excitation dissociates around T_c

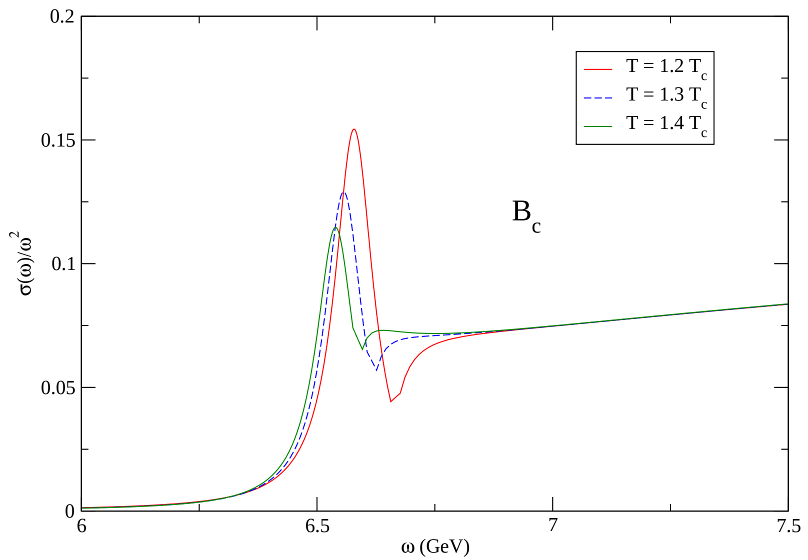




- Fundamental state survives beyond T_c
- Radial excitation dissociates around T_c
- Fundamental state peak decreases gradually as temperature rises beyond T_c

Spectral functions: B_c

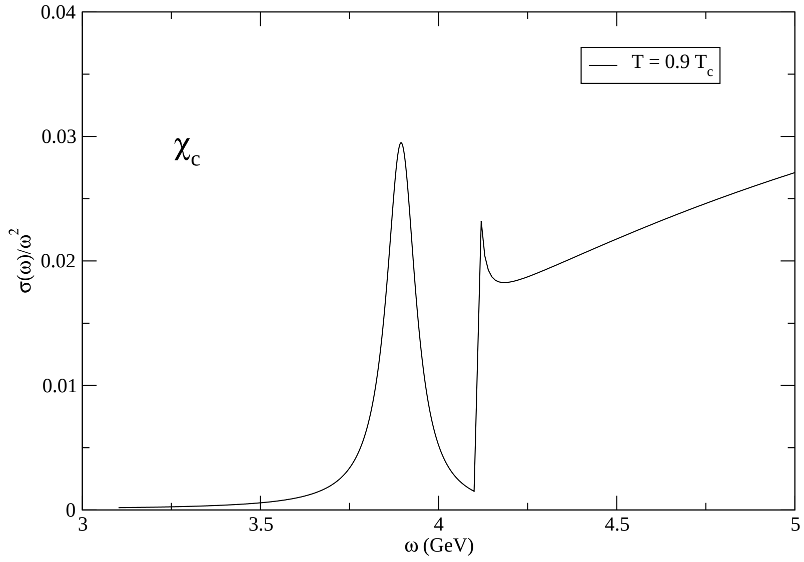




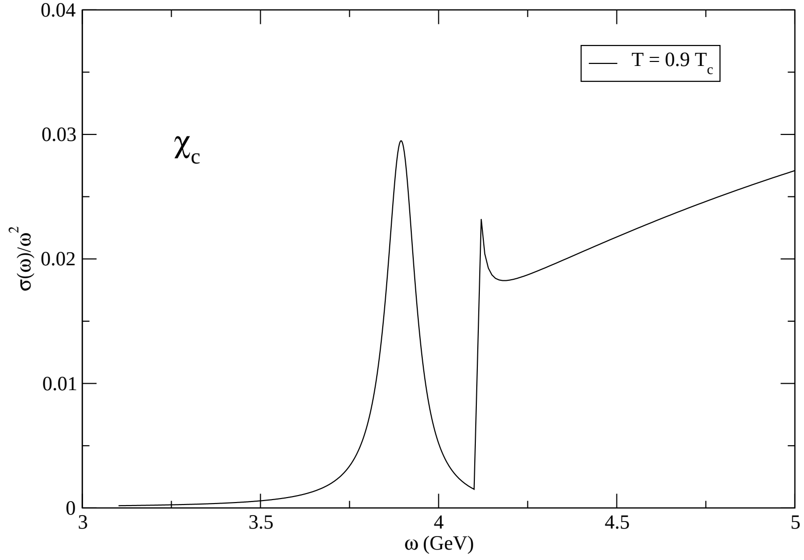
- Fundamental state survives beyond T_c
- Radial excitation dissociates around T_c
- Fundamental state peak decreases gradually as temperature rises beyond T_c
- The peaks shift as the mass changes with temperature

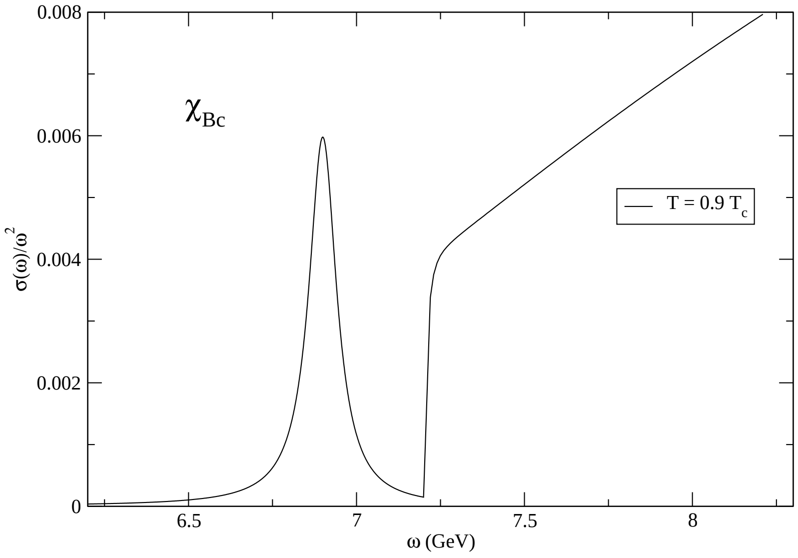
Spectral functions: P wave states

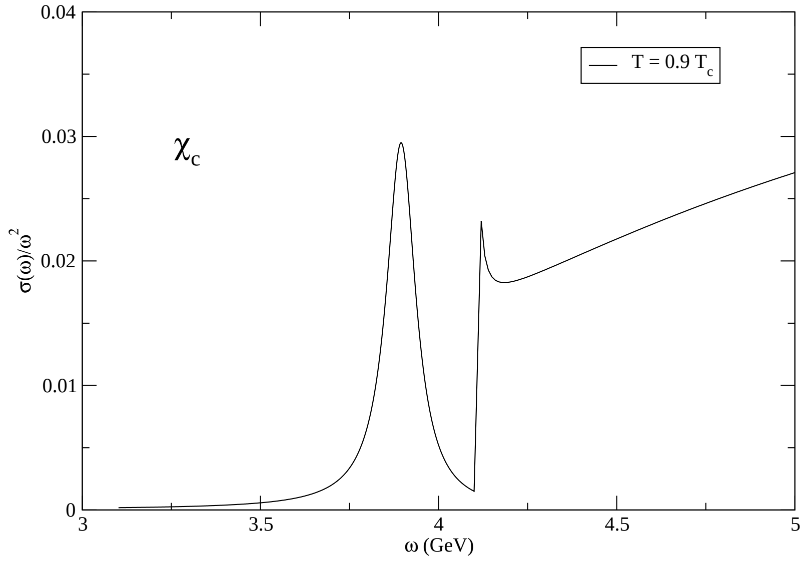
Spectral functions: P wave states

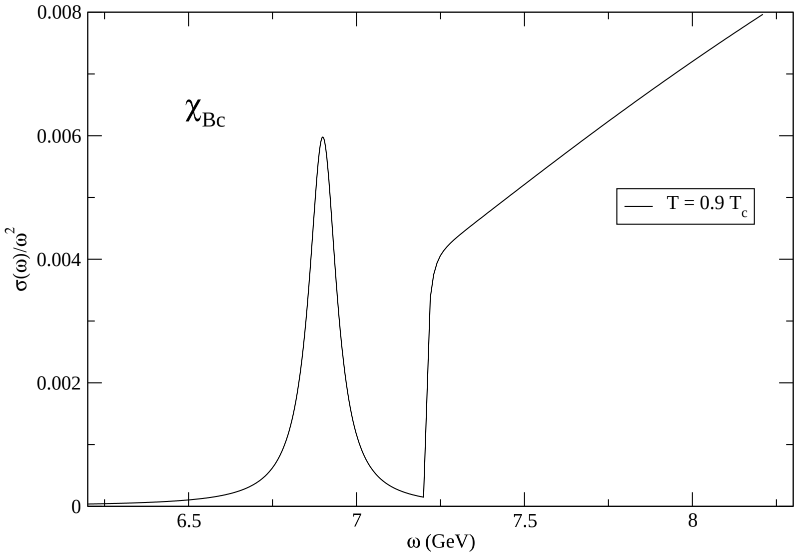


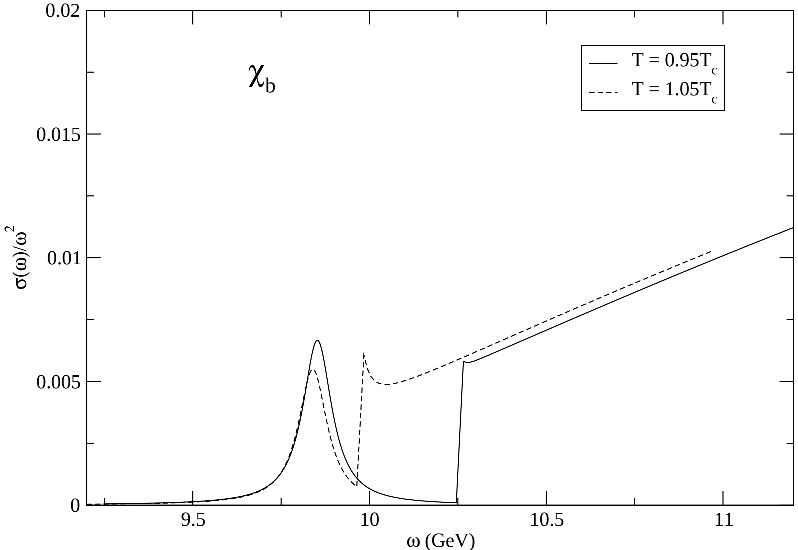
Spectral functions: P wave states






0.04
0.03
0.02
0.01
0
3
3.5
4
4.5
5
$\sigma(\omega)/\omega^2$
ω (GeV)
χ_c
T = 0.9 T_c


0.008
0.006
0.004
0.002
0
6.5
7
7.5
8
$\sigma(\omega)/\omega^2$
ω (GeV)
χ_{Bc}
T = 0.9 T_c


0.02
0.015
0.01
0.005
0
9.5
10
10.5
11
$\sigma(\omega)/\omega^2$
ω (GeV)
χ_b
T = 0.95T_c
T = 1.05T_c

Summing up...

Summing up...

- Importance of the study of heavy mesons in the QGP

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.
- Versatility of the developed model $\longrightarrow$

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.
- Versatility of the developed model $\longrightarrow$
  - Straightforward extension to different bound states

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.
- Versatility of the developed model $\longrightarrow$
  - Straightforward extension to different bound states
  - Immediate extension to lattice data for $N_f \neq 2$

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.
- Versatility of the developed model $\longrightarrow$
  - Straightforward extension to different bound states
  - Immediate extension to lattice data for $N_f \neq 2$
- Comparison with other results:

Summing up...

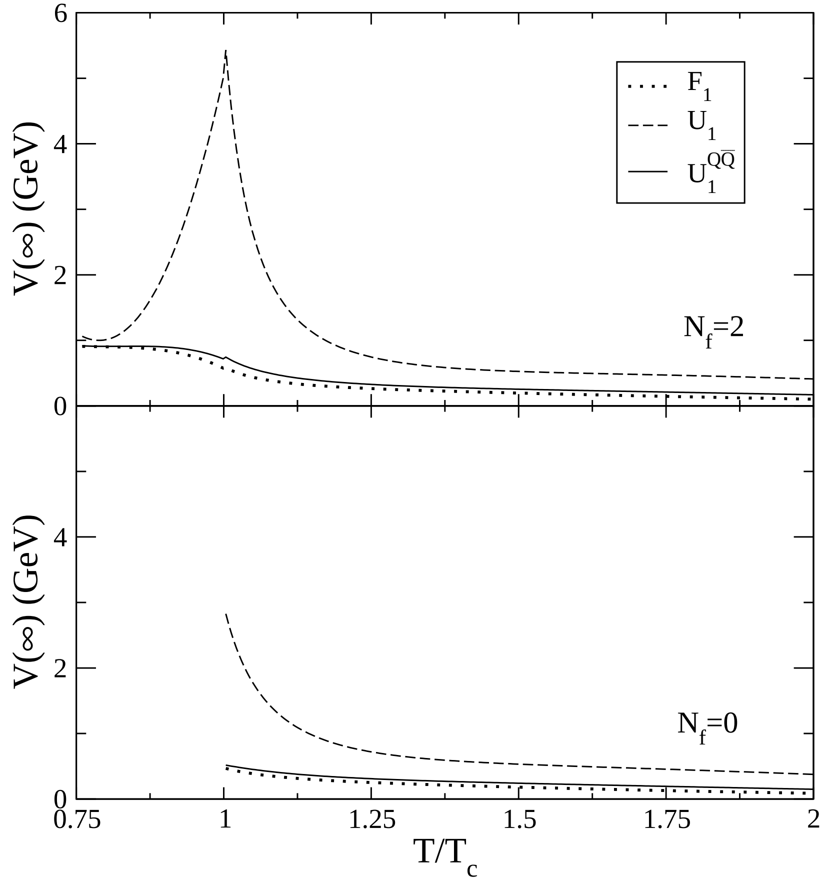
- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.
- Versatility of the developed model $\longrightarrow$
  - Straightforward extension to different bound states
  - Immediate extension to lattice data for $N_f \neq 2$
- Comparison with other results:
  - Dissociation temperatures $\longrightarrow$ Consistent with lattice QCD

Summing up...

- Importance of the study of heavy mesons in the QGP
- Limits of the lattice QCD approach $\longrightarrow$ Potential models
- Integration of the Schroedinger equation $\longrightarrow$
  - Masses, dissociation temperatures, spectral functions.
- Versatility of the developed model $\longrightarrow$
  - Straightforward extension to different bound states
  - Immediate extension to lattice data for $N_f \neq 2$
- Comparison with other results:
  - Dissociation temperatures $\longrightarrow$ Consistent with lattice QCD
  - Spectral functions $\longrightarrow$ harder confrontation with lattice QCD

-

Not enough yet?



Wong's prescription for the potential

$$\epsilon^{(1)}_{\rm QGP}(\vec{x}) \equiv \frac{dU^{(1)}_{QGP}}{dV}(\vec{x}) = T\frac{dS_1}{dV}(\vec{x}) - p^{(1)}(\vec{x})$$

$$\frac{p^{(1)}(\vec{x})}{\epsilon^{(1)}_g(\vec{x})/3} = a(T) \; (\text{Local energy density})$$

$$\frac{dU^{(1)}_g}{dV}(\vec{x}) = \frac{3}{3+a(T)}\frac{TdS_1}{dV}(\vec{x})$$

$$U^{(1)}_g(\vec{r},T) = \int d\vec{x}\,\frac{dU^{(1)}_g}{dV}(\vec{x}) = \frac{3}{3+a(T)}TS_1(\vec{r},T)$$

$$U^{(1)}_g(\vec{r},T) - U_{g0}(T) = \frac{3}{3+a(T)}\{U_1(\vec{r},T) - F_1(\vec{r},T)\}$$

Wong's prescription II

$$U_1(\vec{r},T) = U^{(1)}_{Q\bar{Q}}(\vec{r},T) + U^{(1)}_{g}(\vec{r},T) - U_{g0}(T)$$

From which

$$U^{(1)}_{Q\bar{Q}}(\vec{r},T) = \frac{3}{3+a(T)}[F_1(\vec{r},T) - U_1(\vec{r},T)] + U_1(\vec{r},T)$$

$$= \frac{3}{3+a(T)}F_1(\vec{r},T) + \frac{a(T)}{3+a(T)}U_1(\vec{r},T)$$

The potential then is

$$U^{(1)}_{Q\bar{Q}}(\vec{r},T) - U^{(1)}_{Q\bar{Q}}(\vec{r}\to\infty,T)$$

$$= f_F(T)\,[F_1(\vec{r},T) - F_1(\vec{r}\to\infty,T)]$$

$$+ f_U(T)\,[U_1(\vec{r},T) - U_1(\vec{r}\to\infty,T)]$$