Quarkonium Working Group 2011

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BOTTOMONIUM:FROM HADRONIC MATTER TO QUARK GLUON PLASMA

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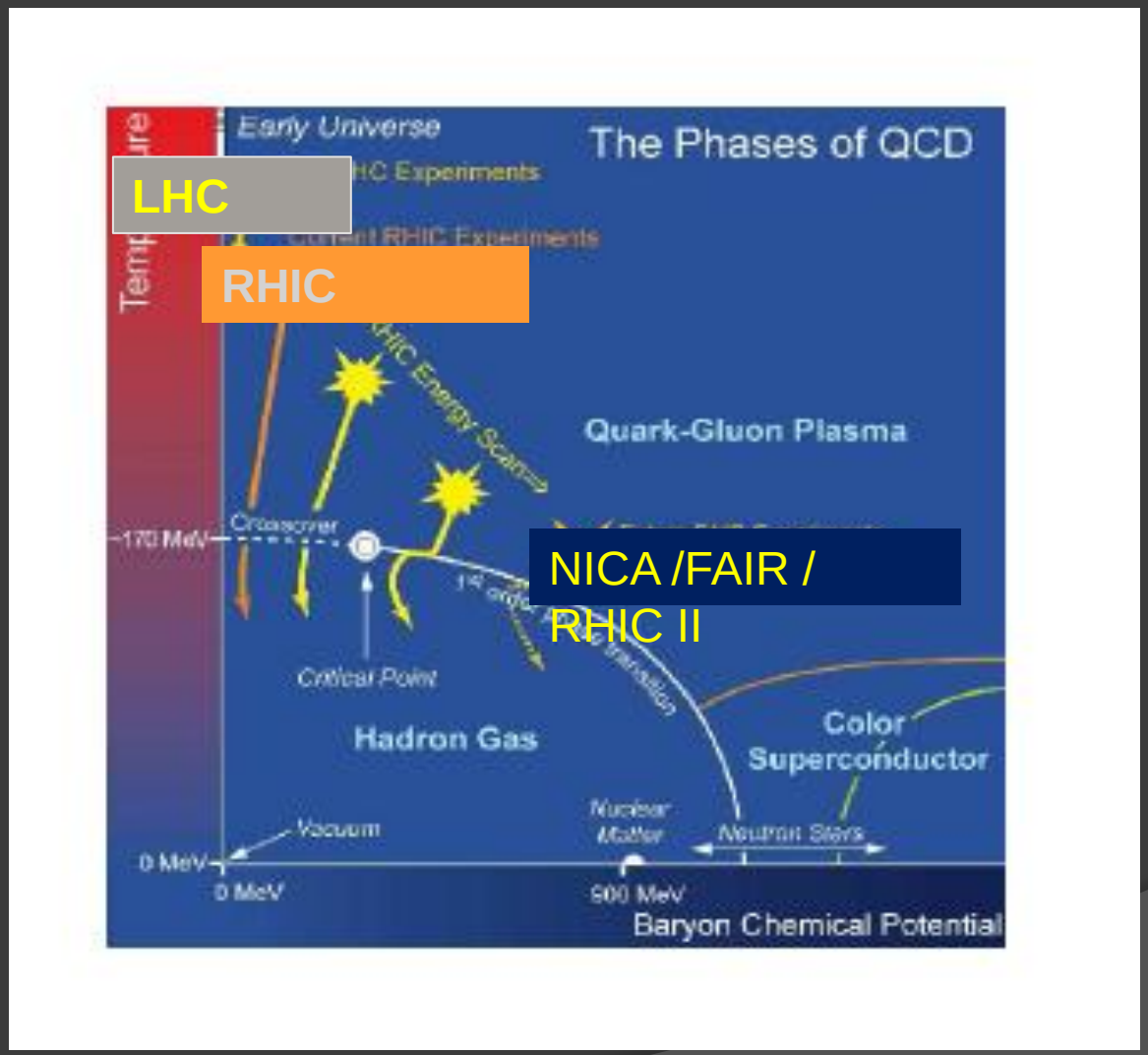
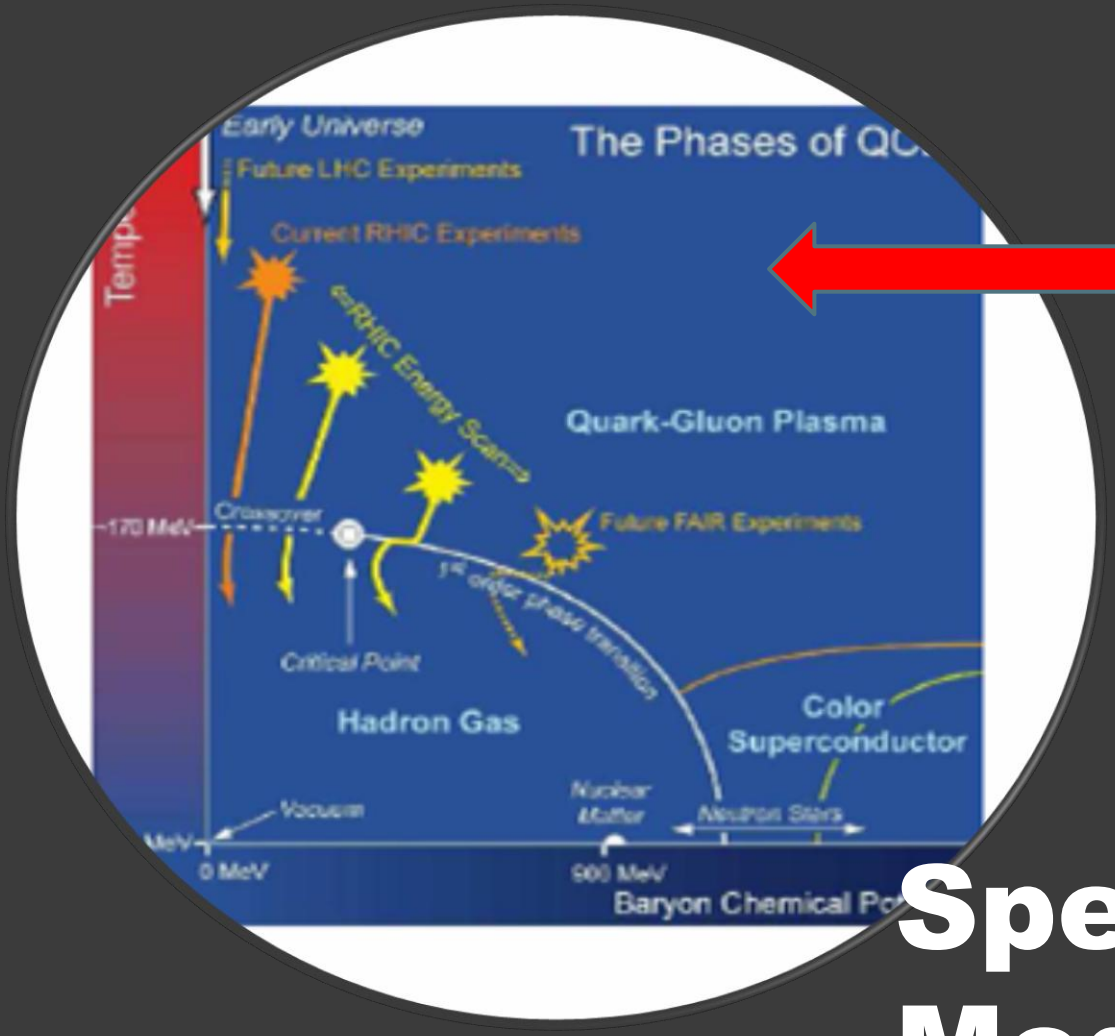
arXiv:1109.4489

The QCD Phase Diagram



US NSAC Long RangePlan (adapted)



Quark Gluon Plasma

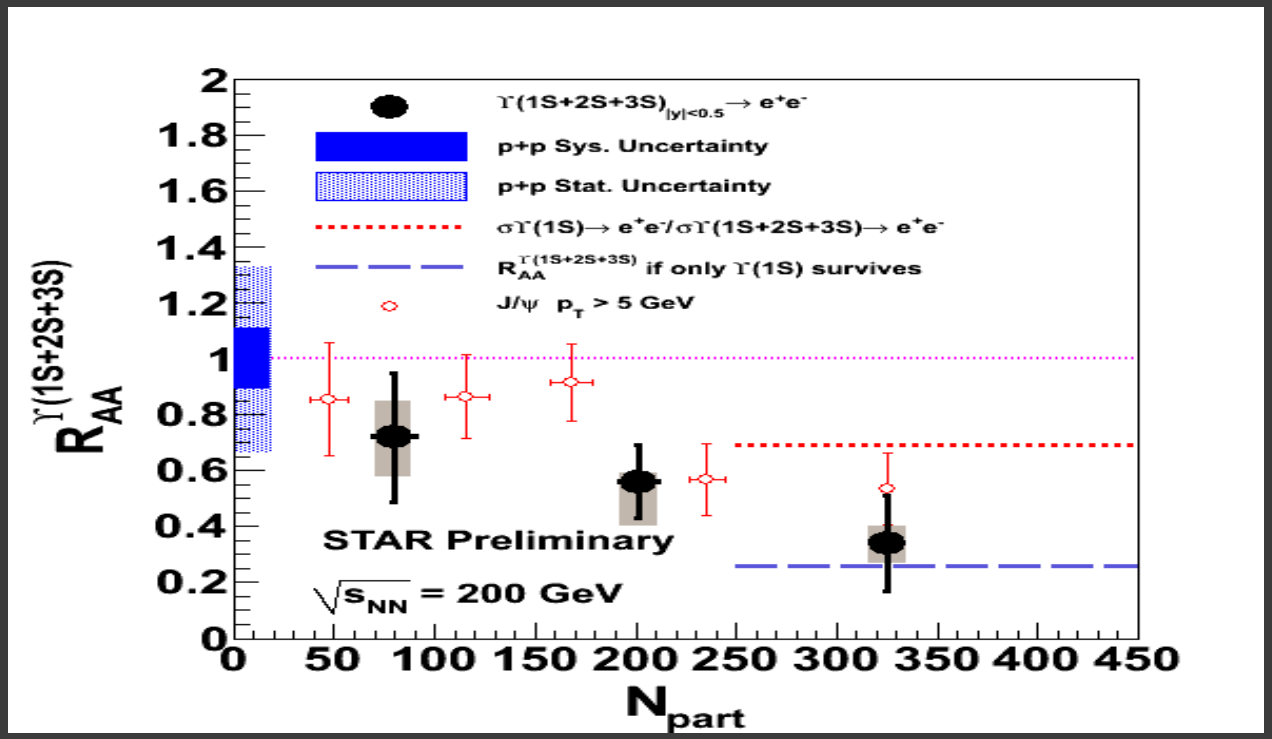
Deconfinement

Chiral Symmetry Restoration

Spectrum Modifications

First measurements of Upsilon suppression by STAR

Rosi Reed @ QM2011



Further experimental results today:

Mironov (CMS) Grabowska-Bold(ATLAS)

Martinez(Alice) Reed (STAR)

A short History

The Theory : Charmonium suppression predicted
Matsui-Satz 1986

SPS : Charmonium suppression observed –
, Quark Gluon Plasma discovered!!

RHIC: Not really...previous theoretical analysis too crude..
Charmonium suppression is not enough .. Competing effects

LHC + RHIC: High precision Charmonium AND Bottomonium physics – calling for a better theoretical understanding

Temperature range: Experiments and our Bottomonium study

700-800 MeV (LHC expected)

500-600 MeV (LHC current)

350 MeV (RHIC-STAR)

Tc 170 MeV

Lattice Bottomonium 70 MeV – 360 MeV

OUTLINE

Five Steps to Bottomonium:

- 1. Use full relativistic dynamics for up and down quarks
- 2. Treat bottom with NRQCD
- 3. Make the most of correlators in Euclidean space.
- 4. MEM analysis → Spectral functions
- 5. Masses, Width and Effective models

Summary

Step 1:

Full Relativistic Lattice QCD for light quarks with asymmetric gauge couplings to increase number of points in t-direction

N_s	N_τ	T(MeV)	T/T_c	$N_{\rm cfg}$
12	80	90	0.42	250
12	32	230	1.05	1000
12	28	263	1.20	1000
12	24	306	1.40	500
12	20	368	1.68	1000
12	18	408	1.86	1000
12	16	458	2.09	1000

Step 2 : NRQCD for bottom quarks

Check: Zero Temperature Results

state	$a_\tau \Delta E$	Mass (MeV)	Exp. (MeV) [34]
$1^1S_0(\eta_b)$	0.118(1)	9438(7)	9390.9(2.8)
$2^1S_0(\eta_b(2S))$	0.197(2)	10009(14)	-
$1^3S_1(\Upsilon)$	0.121(1)	9460*	9460.30(26)
$2^3S_1(\Upsilon')$	0.198(2)	10017(14)	10023.26(31)
$1^1P_1(h_b)$	0.178(2)	9872(14)	-
$1^3P_0(\chi_{b0})$	0.175(4)	9850(28)	9859.44(42)(31)
$1^3P_1(\chi_{b1})$	0.176(3)	9858(21)	9892.78(26)(31)
$1^3P_2(\chi_{b2})$	0.182(3)	9901(21)	9912.21(26)(31)

NRQCD for bottom quarks:

NB Propagators initial value problem

$$G(\mathbf{x}, \tau = 0) = S(\mathbf{x}),$$

$$G(\mathbf{x}, \tau = a_\tau) = \left(1 - \frac{H_0}{2n}\right)^n U_4^\dagger(\mathbf{x}, 0) \left(1 - \frac{H_0}{2n}\right)^n G(\mathbf{x}, 0),$$

Temperature (= boundary condition) dependence is only due to the thermal medium!

NRQCD is still valid in our T range

$$\omega = 2M + \omega'$$

$$M \gg T$$

STEP 3 : Analysis of propagators in Euclidean time

Bound states for S and P waves

$$G(\tau) \sim \exp(-\Delta E \tau)$$

Free behaviour for S and P waves

$$G_S(\tau) \sim \int \frac{d^3p}{(2\pi)^3} \exp(-2E_{\mathbf{p}}\tau) \sim \tau^{-3/2},$$

$$G_P(\tau) \sim \int \frac{d^3p}{(2\pi)^3} \mathbf{p}^2 \exp(-2E_{\mathbf{p}}\tau) \sim \tau^{-5/2},$$

Laine et al 2010

$$E_{\mathrm{p}} = \mathrm{p}^2/2M$$

Υ and χ_b in the plasma :RESULTS

Bound states

$$G(\tau) \sim \exp(-\Delta E \tau),$$

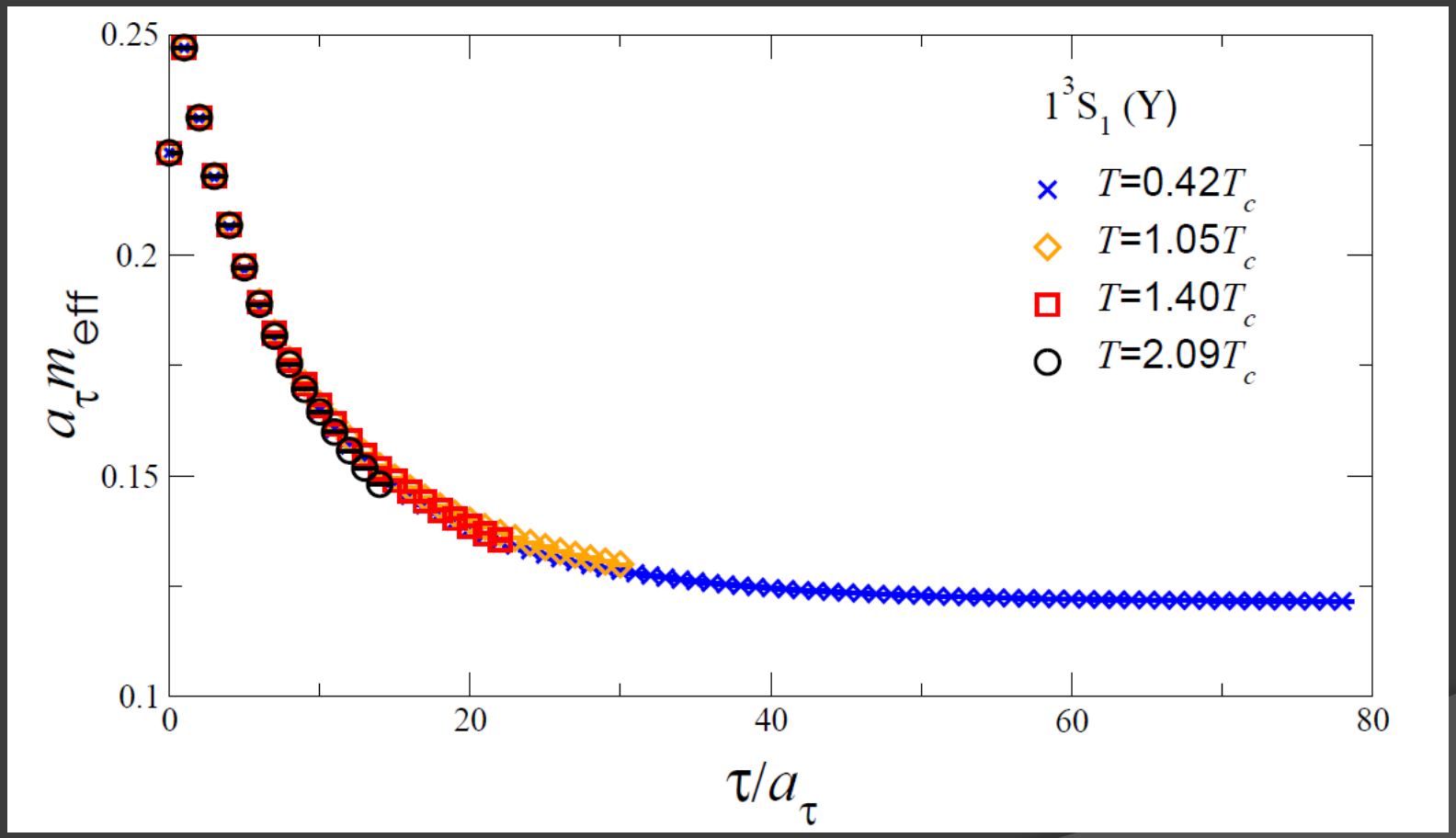
$$m_{\rm eff}(\tau) = -\log[G(\tau)/G(\tau - a_\tau)],$$

Free quarks

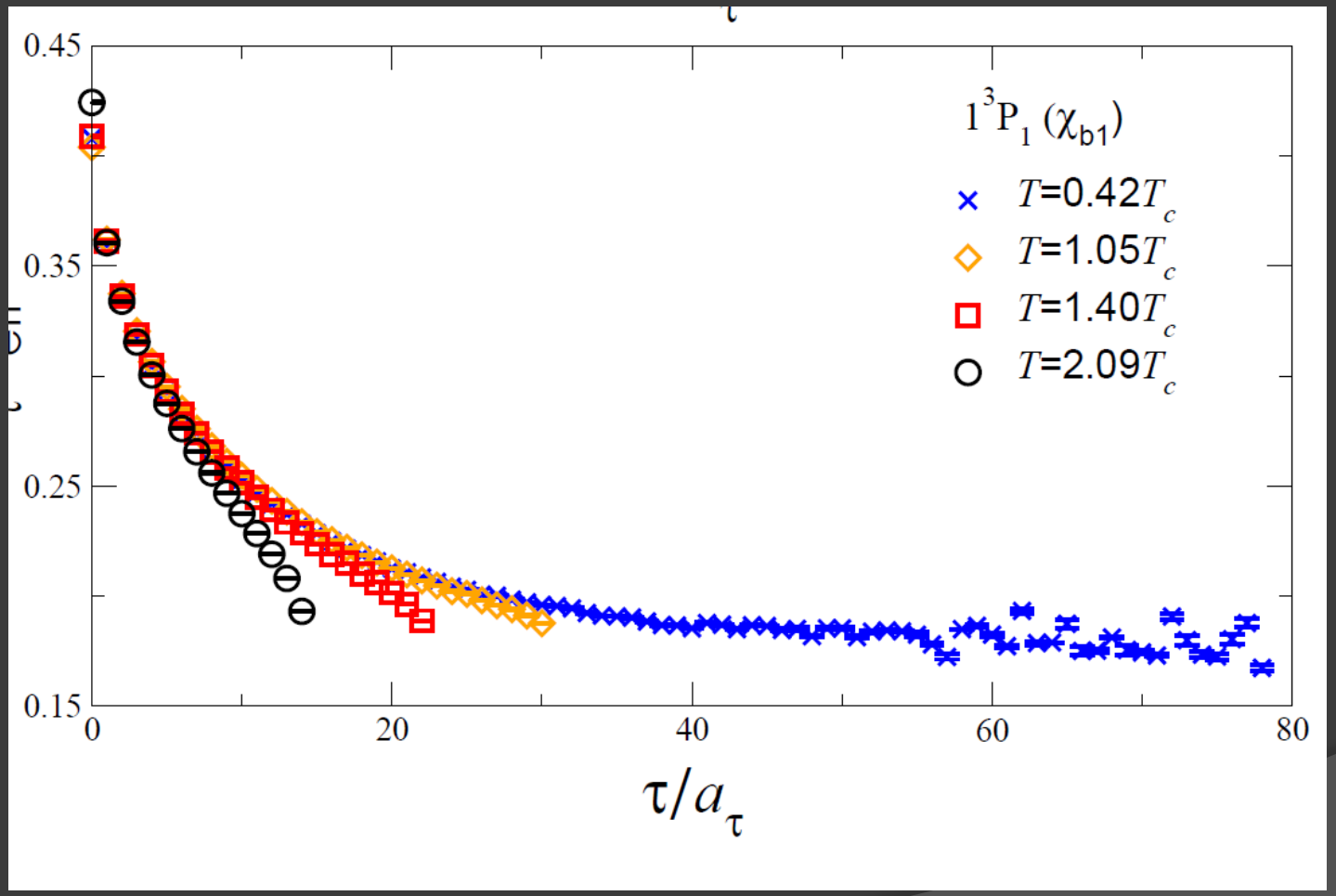
$$G(\tau) \sim \tau^{-\gamma}$$

$$\gamma_{\rm eff}(\tau) = -\tau \frac{G'(\tau)}{G(\tau)} = -\tau \frac{G(\tau + a_\tau) - G(\tau - a_\tau)}{2 a_\tau G(\tau)},$$

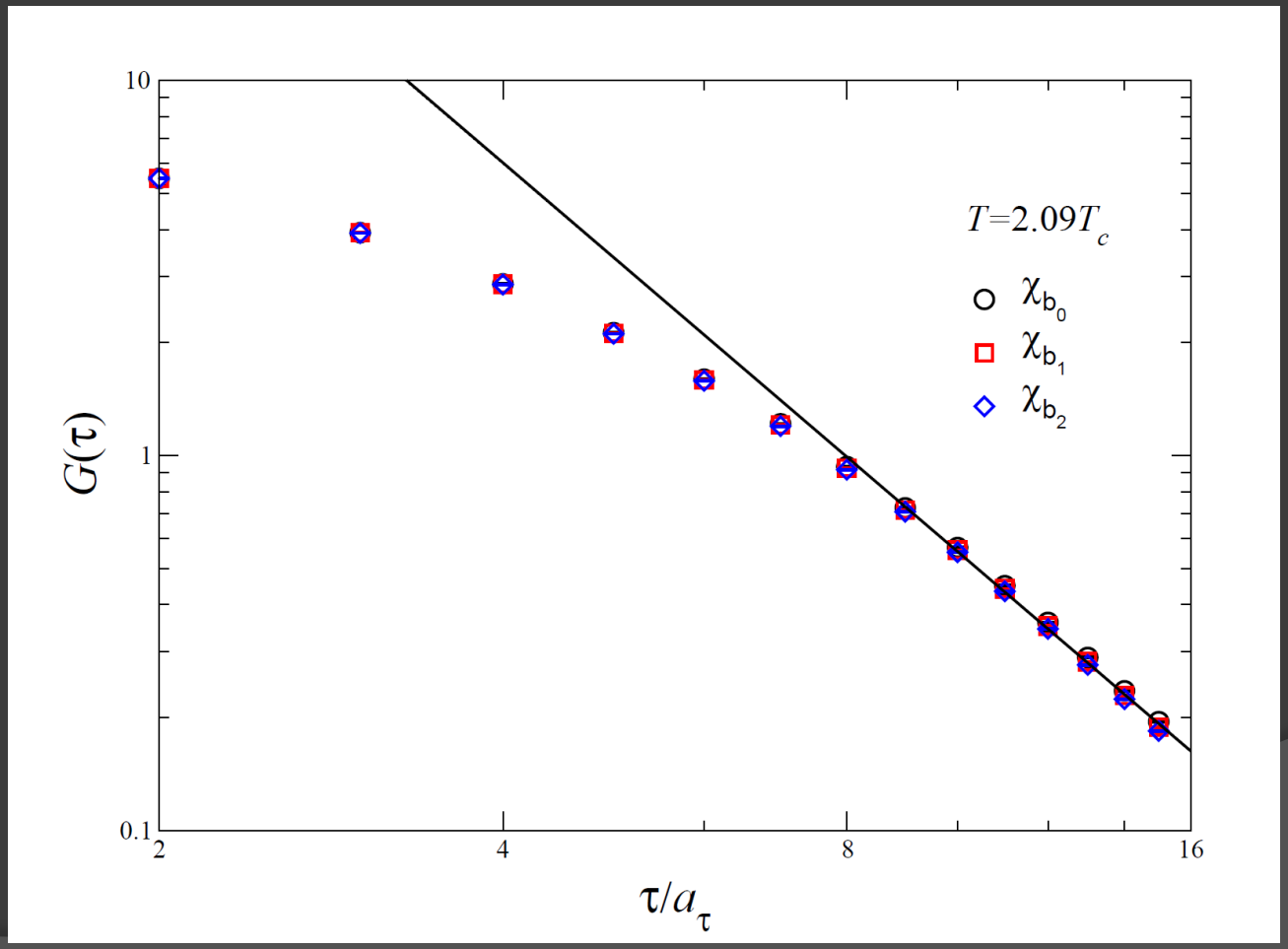
Effective mass for the Υ



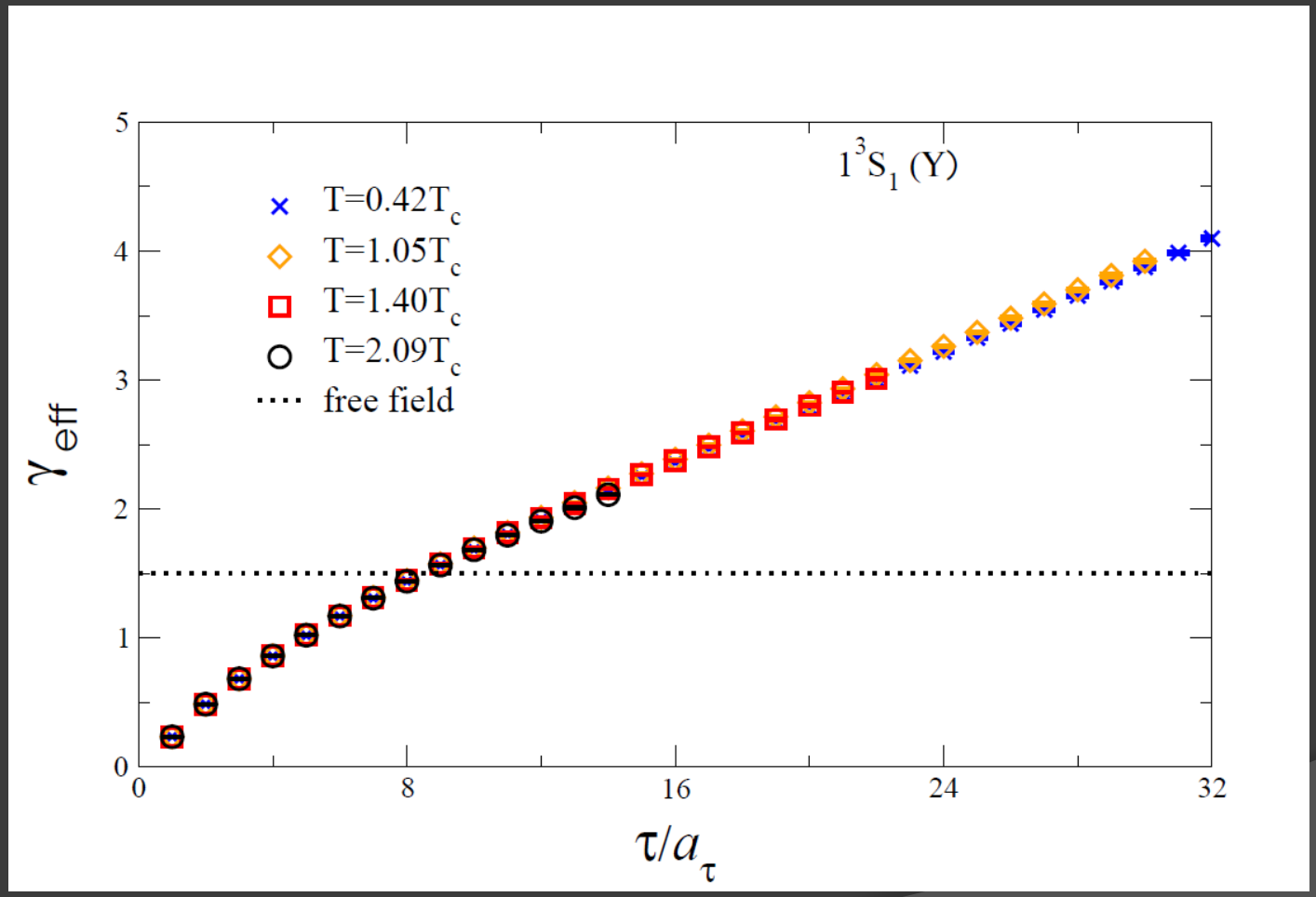
Effective mass for the χ



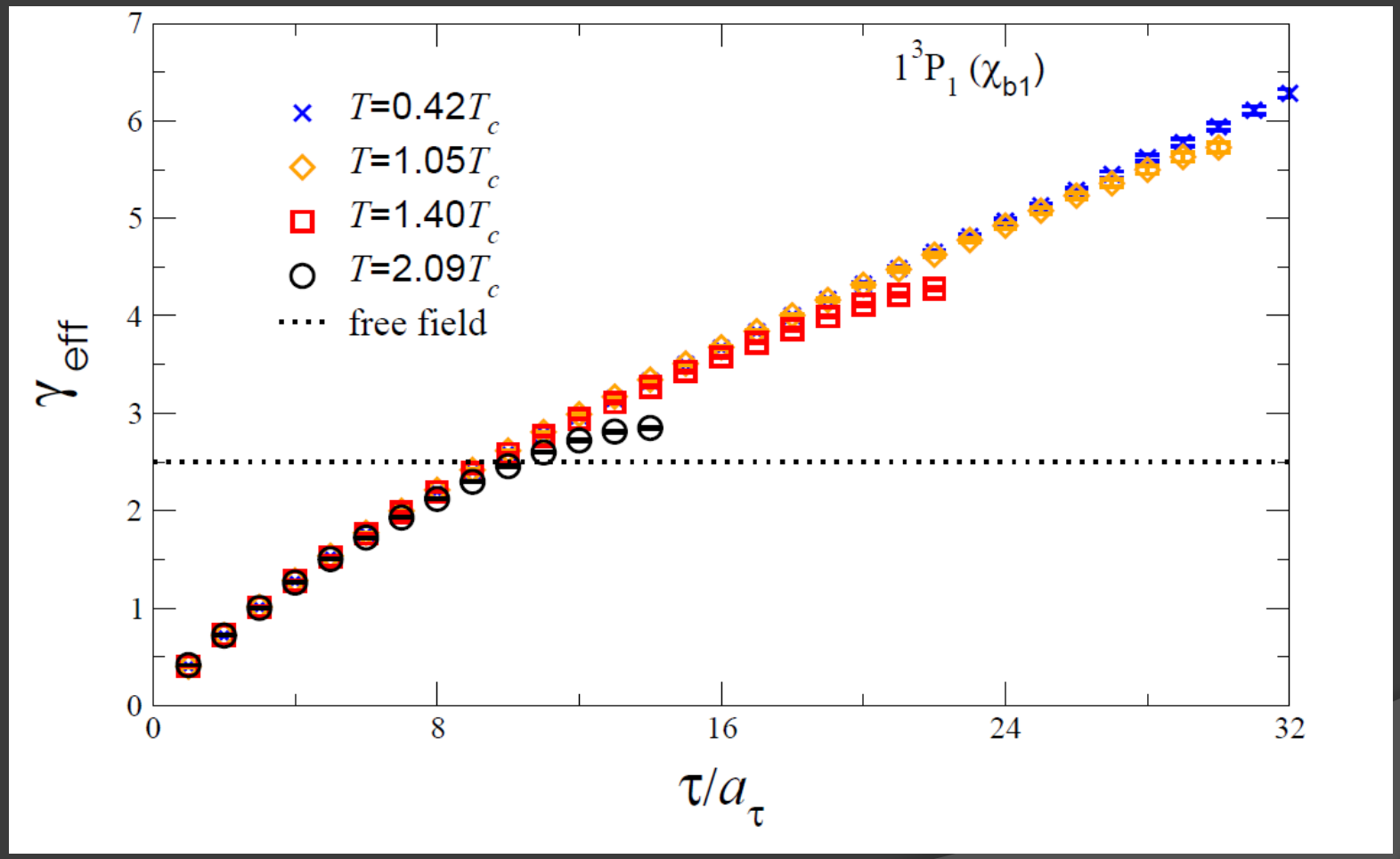
χ propagators and power law at T = 2.09 Tc : consistent with a free behaviour!



Y and (NO) free behaviour



χ free behaviour at T = 2.09Tc



Step 4: Spectral Functions

$$G(\tau) = \int_0^\infty \frac{d\omega}{\pi} \frac{\cosh\left[\omega(\tau - 1/2T)\right]}{\sinh\left(\omega/2T\right)} \rho(\omega).$$

Nontrivial spectral weight at small ω yields a constant τ-independent contribution to the correlator, which must be treated with care

Laine, Petreckzy et al.

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$$G(\tau) = \int_{-2M}^\infty \frac{d\omega'}{\pi} \exp(-\omega'\tau)\rho(\omega') \qquad \text{(NRQCD)}$$

Spectral Functions

NRQCD PLUS'es:

No Temperature dependence in the kernel

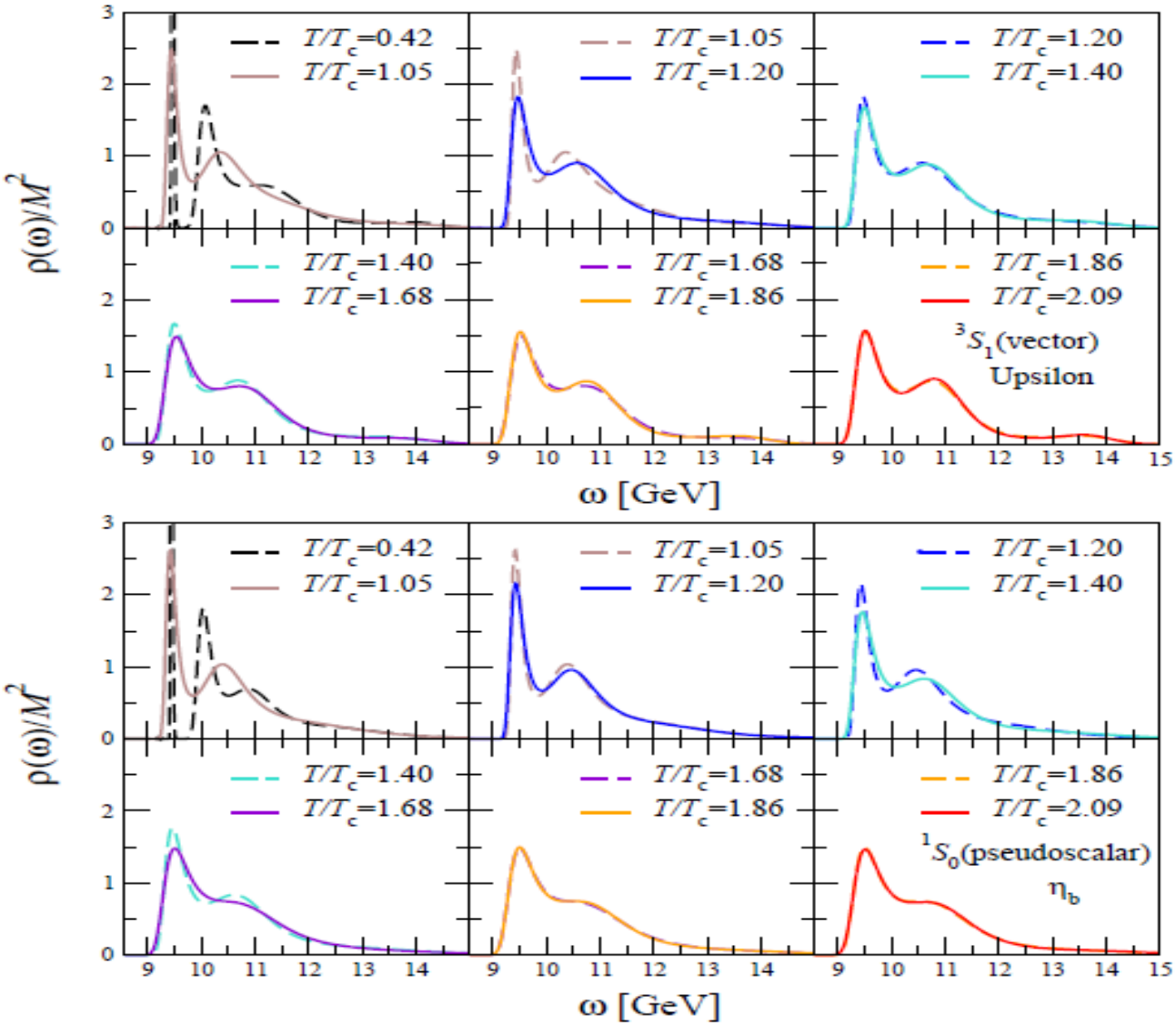
No problem with zero modes

Easier MEM analysis

Temperature dependence of the Euclidean correlators entirely dynamical

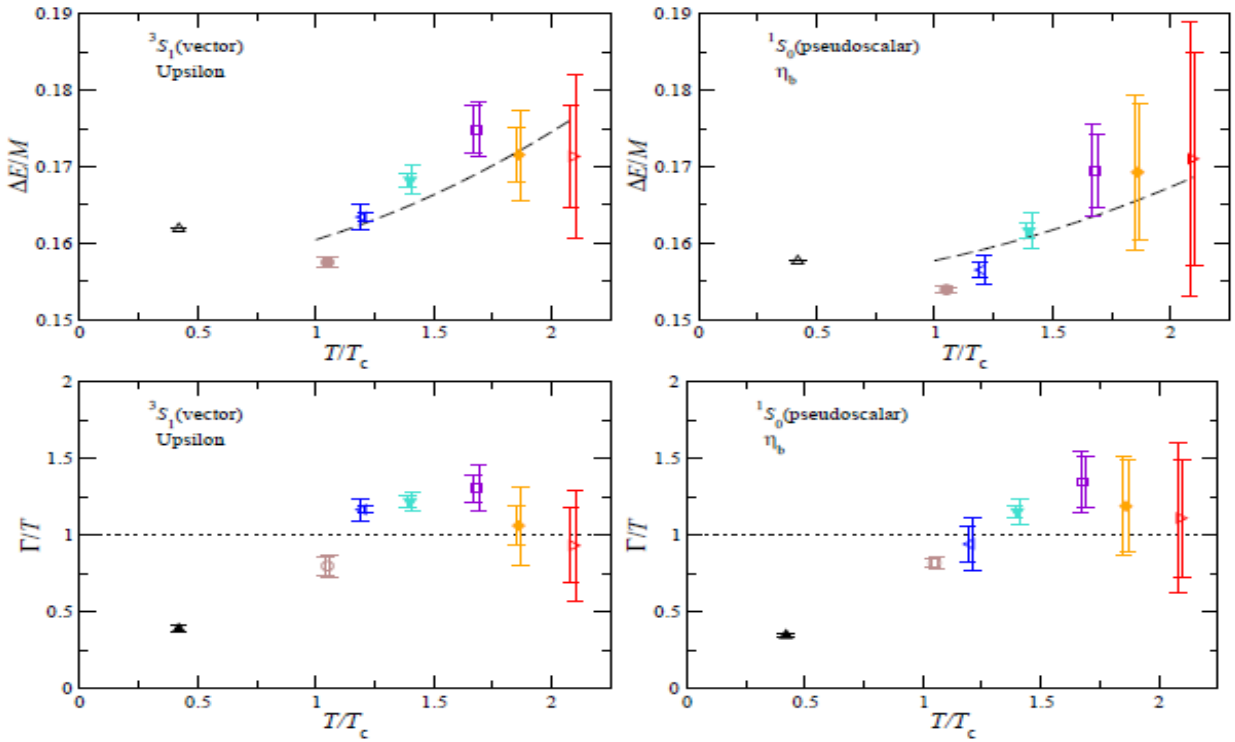
$$G(\tau) = \int_{-2M}^{\infty} \frac{d\omega'}{\pi} \exp(-\omega'\tau)\rho(\omega') \qquad \text{(NRQCD)}$$

NRQCD spectral functions – S waves



Step 5 : Results for Masses and Widths

S-Waves



Dashed line :
fit motivated by

N. Brambilla, M. A. Escobedo, J. Ghiglieri, J. Soto, A. Vairo, JHEP 1009 (2010) 038 [arXiv:1007.4156 [hep-ph]].

Comparision with weak coupling expansion [N.Brambilla et al.2010]

$$\frac{\Gamma}{T} = \frac{1156}{81}\alpha_s^3 \simeq 14.27\alpha_s^3,$$

$$\alpha_s \sim 0.4,$$

$$\frac{\delta E_{\text{thermal}}}{M} = 5.93\alpha_s \left(\frac{T_c}{M}\right)^2 \left(\frac{T}{T_c}\right)^2 \sim 0.0046 \left(\frac{T}{T_c}\right)^2 .$$

Fit to:

$$\frac{\Delta E}{M} = c + 0.0046 \left(\frac{T}{T_c}\right)^2$$

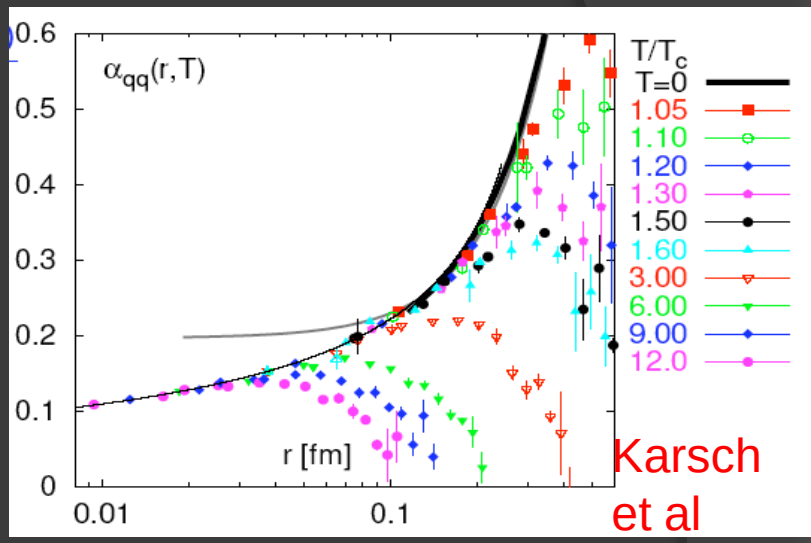
Q Qbar interactions at High T, Potential, Spectral functions

Running coupling at high T physically interesting.

However what makes the QGP strongly interacting not clear yet

Ambiguities in the definition of the potential producing ambiguous results

use



Karsch et al

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
$V(r,T) = U(r,T)$	2.1	1.2	1.1
$V(r,T) = F(r,T)$	1.2	1.0	1.0

From H.Satz

To clarify relation with lattice data compute spectral functions and potential on same configurations

Allton and Skullerud, in progress

Summary

- We have studied the temperature dependence of bottomonium for 0.4 Tc < T < T 2.1 Tc, using nonrelativistic dynamics for the bottom quark and full relativistic QCD for up and down quarks
- Correlators and spectral functions indicate that the Upsilon and η_b fundamental states are insensitive to the temperature in this range
- The χ show a crossover from an exponential decay characterizing the hadronic phase to a power-law behaviour consistent with nearly-free dynamics at 2Tc
- The Upsilon and η_b excited states are no longer visible at temperatures above 1.4 Tc , in agreement with experimental observations at RHIC and LHC