CORTONA 2013
XIV CONVEGNO su PROBLEMI
di FISICA NUCLEARE
TEORICA
29–31 OTTOBRE 2013

M.P. Lombardo
INFN

Quark Gluon Plasma:
from lattice simulations to experimental results

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Quark Gluon Plasma:
from lattice simulations to experimental results

HUGE FIELD OF REASEARCH!!

This talk: *FASTUM Collaboration*

FASTSUM collaboration:

Quark-gluon plasma phenomenology from the lattice

Chris Allton[1,*], Gert Aarts[1], Alessandro Amato[1,2], Wynne Evans[1,3], Pietro Giudice[1,4], Simon Hands[1], Aoife Kelly[5], Seyong Kim[6], Maria-Paola Lombardo[7], Sinead Ryan[8], Jon-Ivar Skullerud[5], Tim Harris[8]

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[5] Department of Mathematical Physics, NUIM, Maynooth, Co. Kildare, Ireland
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[8] School of Mathematics, Trinity College, Dublin 2, Ireland
[*] Speaker

arXiv:1310.5135

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Quark Gluon Plasma:
from lattice simulations to experimental results

Case study: Bottomonium
as a probe of the deconfined medium

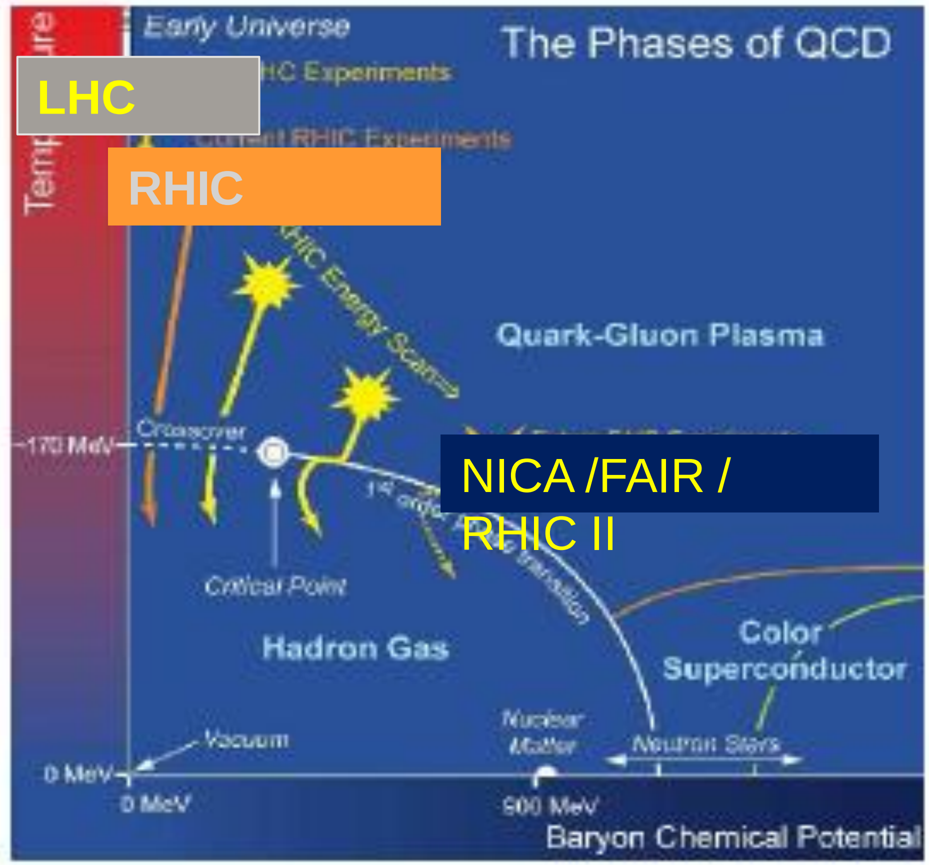
arXiv:1310.5467

JHEP 1303 (2013) 084

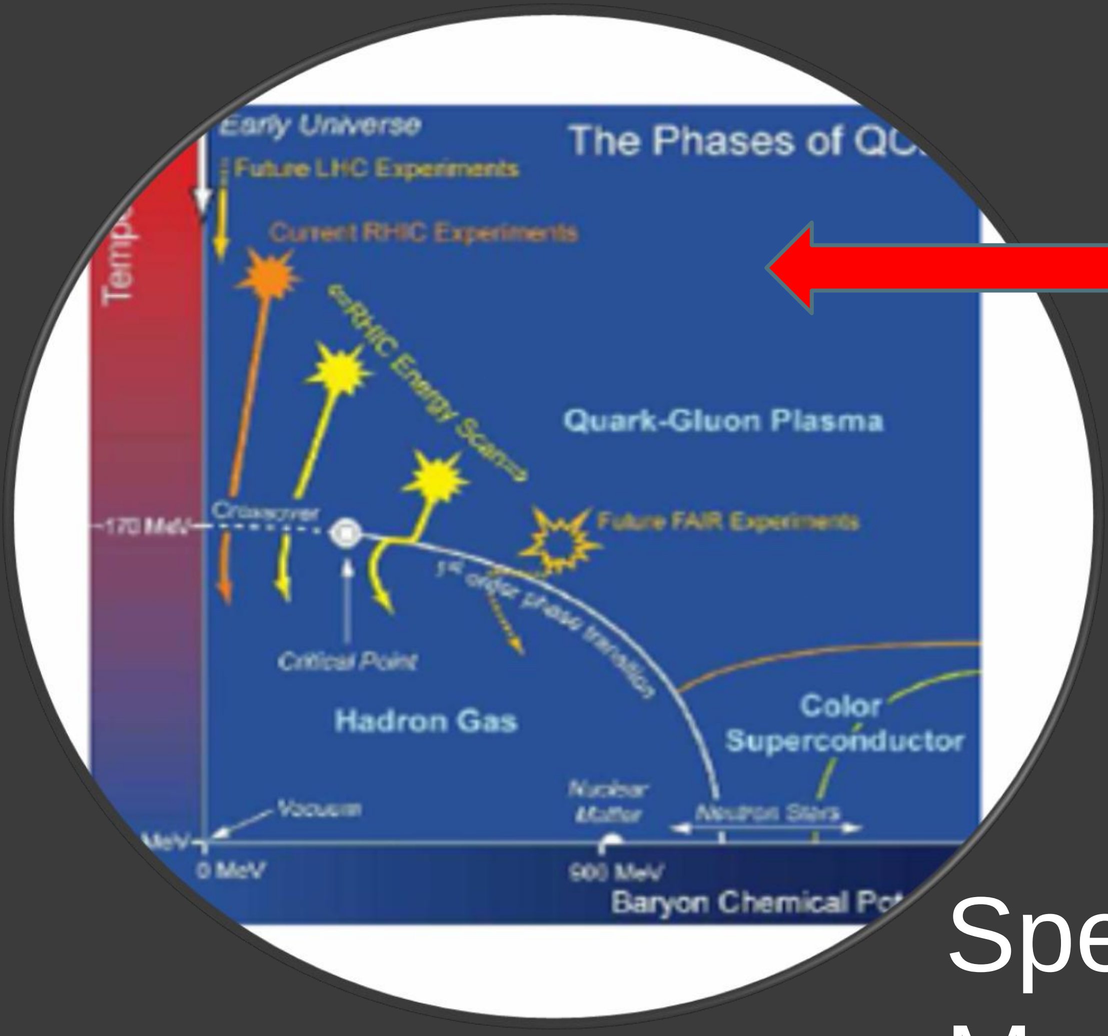
JHEP 1111 (2011) 103

Phys.Rev.Lett. 106 (2011) 061602

QGP in the QCD Phase Diagram



US NSAC Long RangePlan (adapted)



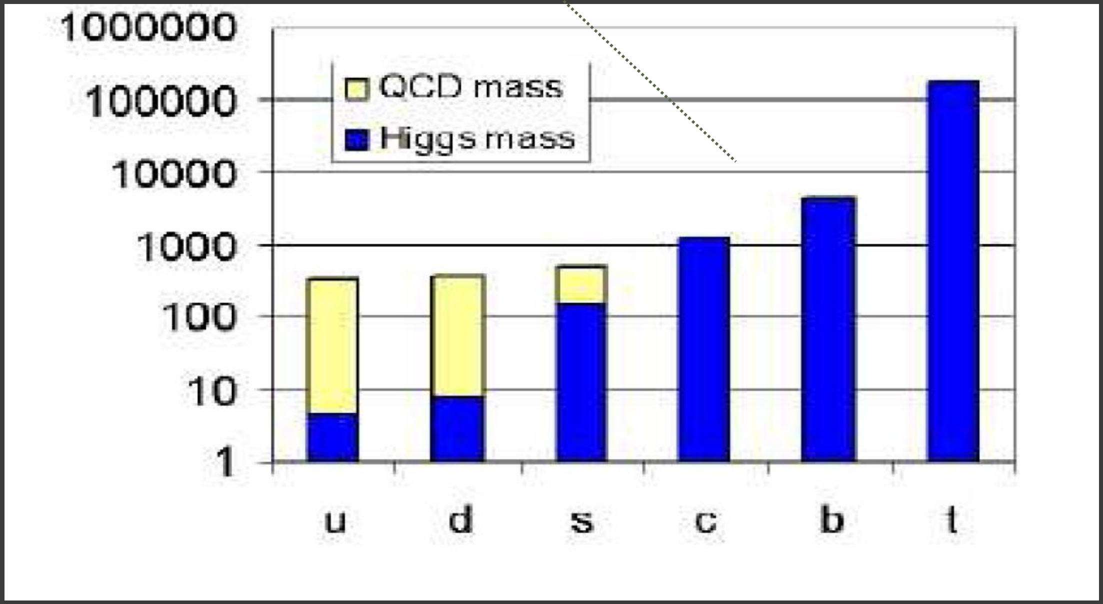
Quark Gluon Plasma

Deconfinement

Chiral Symmetry Restoration

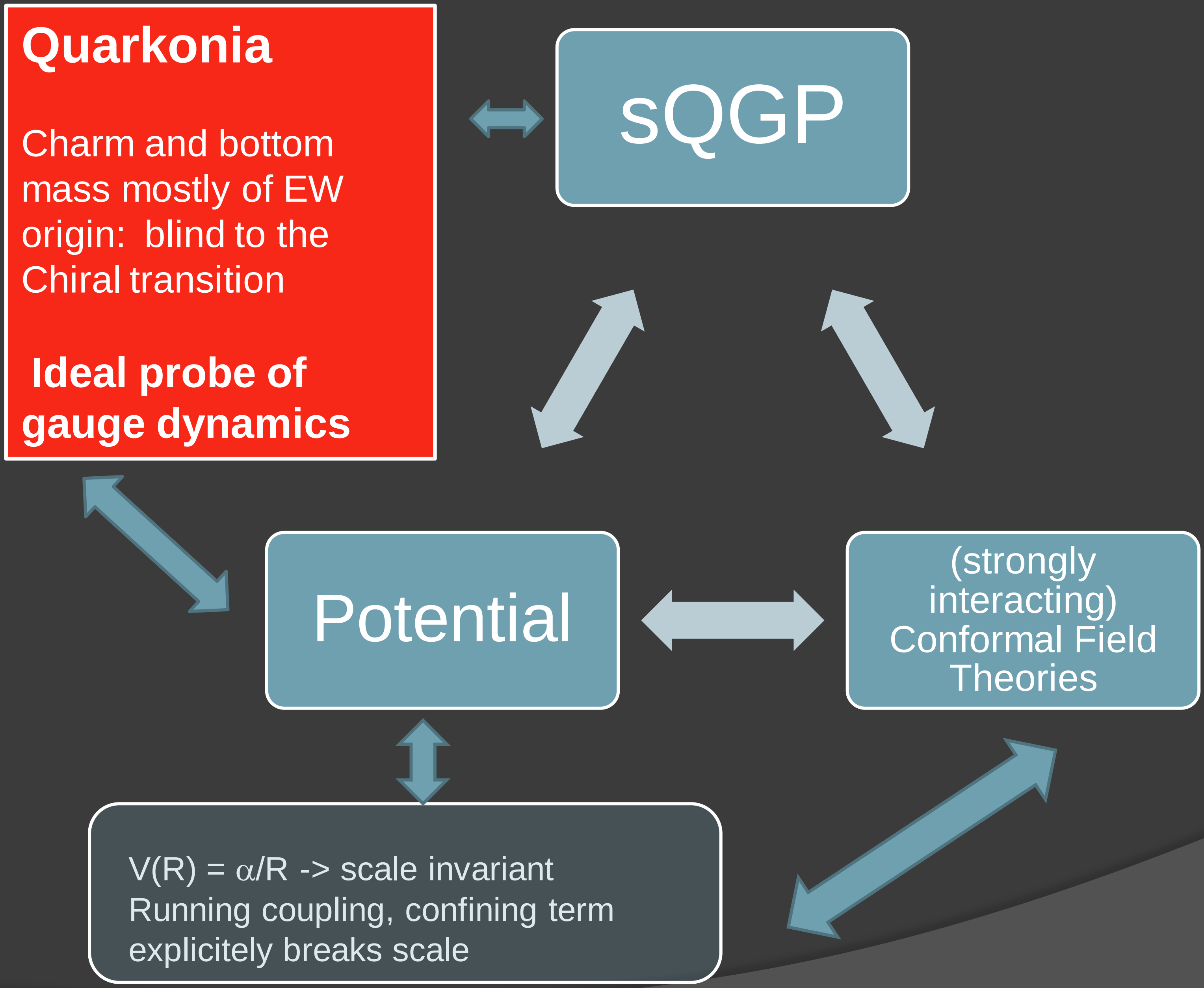
Spectrum Modifications

Charm and Bottom:



Picture from B. Muller

'Blind' to QCD chiral symmetry
Probes of gauge dynamics in the QGP


Quarkonia
Charm and bottom mass mostly of EW origin: blind to the Chiral transition
Ideal probe of gauge dynamics
sQGP
Potential
(strongly interacting) Conformal Field Theories
V(R) = α/R -> scale invariant
Running coupling, confining term explicitely breaks scale

Milestones

The Theory : Charmonium suppression predicted
Matsui-Satz 1986

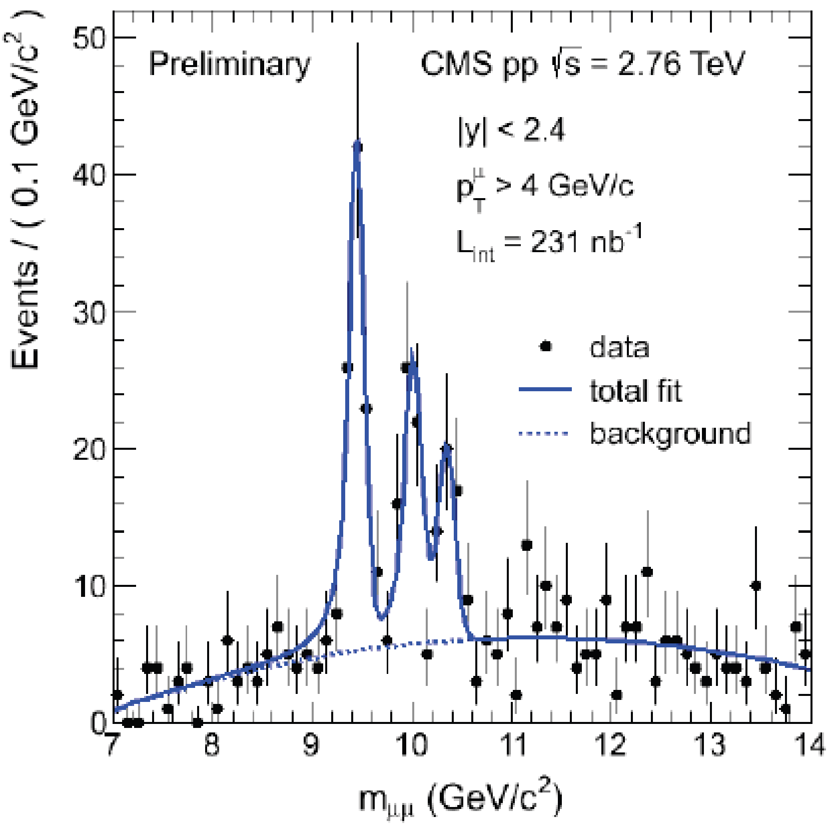
SPS : Charmonium suppression observed –
, Quark Gluon Plasma discovered!!

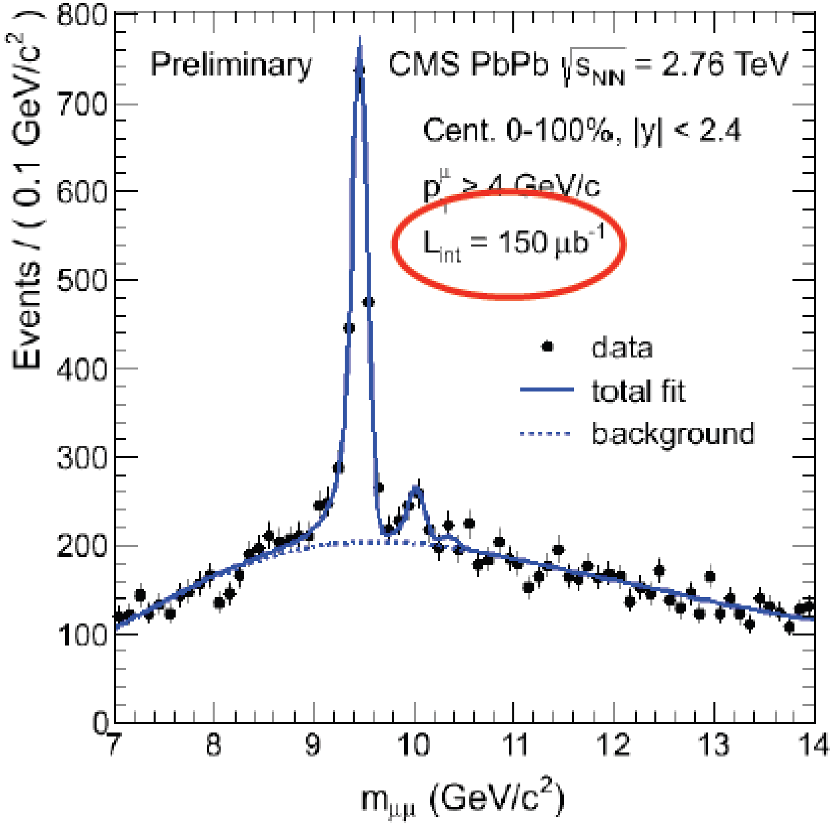
RHIC: Not really…previous theoretical analysis too crude..
Charmonium suppression is not enough .. Competing effects

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

Bottomonia: with 2011 data

pp | CMS-HIN-11-011 | PbPb





$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Ratios not corrected for acceptance and efficiency

Temperatures explored

1 GeV (LHC expected 7 TeV)

500-600 MeV (LHC 2.76 TeV ?)

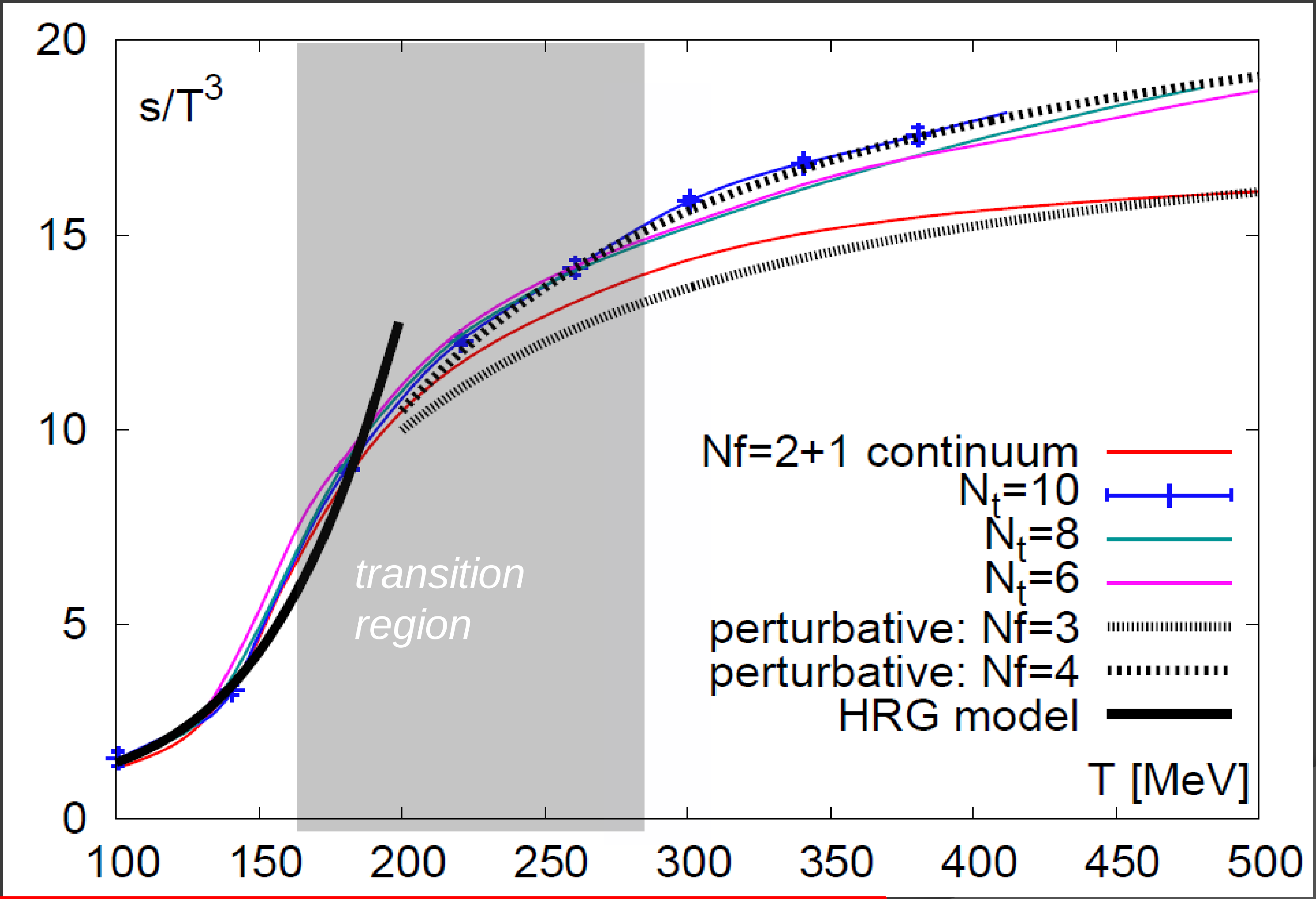
420-500 MeV (LHC 2.76 TeV)

350 MeV (RHIC-STAR)

Tc 170 MeV

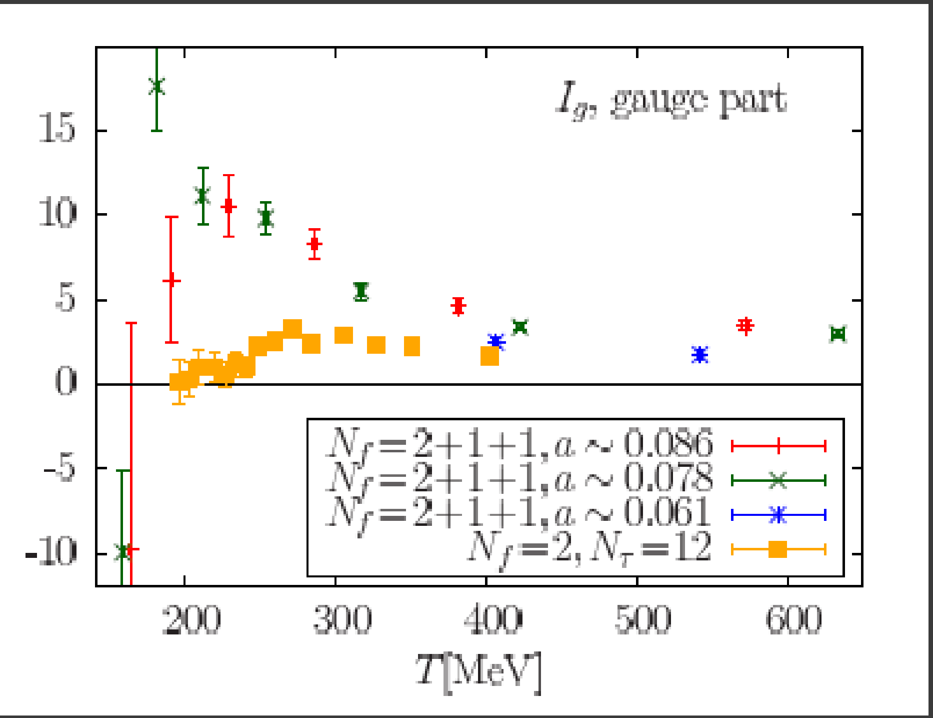
EoS for Nf = 2+1+1

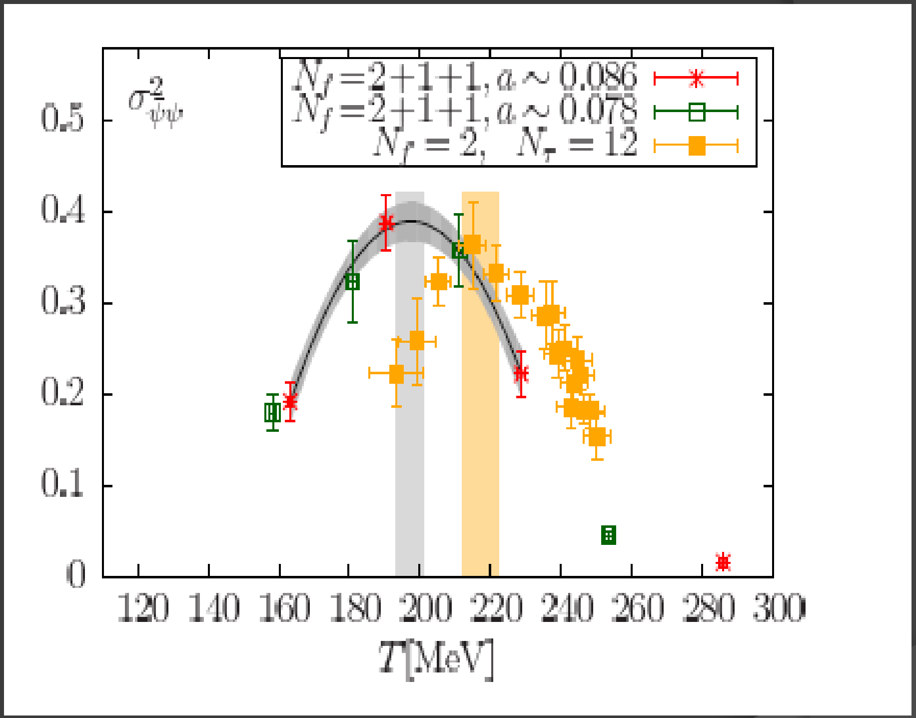
Wuppertal-Budapest 2013



Range of lattice quarkonium results

TmFT (F.Burger,G. Holtzel, M.Ilgenfritz,Michael Mueller-Preussker, M.P.L Lat2013)





Effects of a dynamical second generation

Outline

- QCD potential(s)
- Quarkonia from first principles

  Charmonium

  Bottomonium
- Summary, and a few open questions

Outline

- QCD potential(s)
- Quarkonia from first principles

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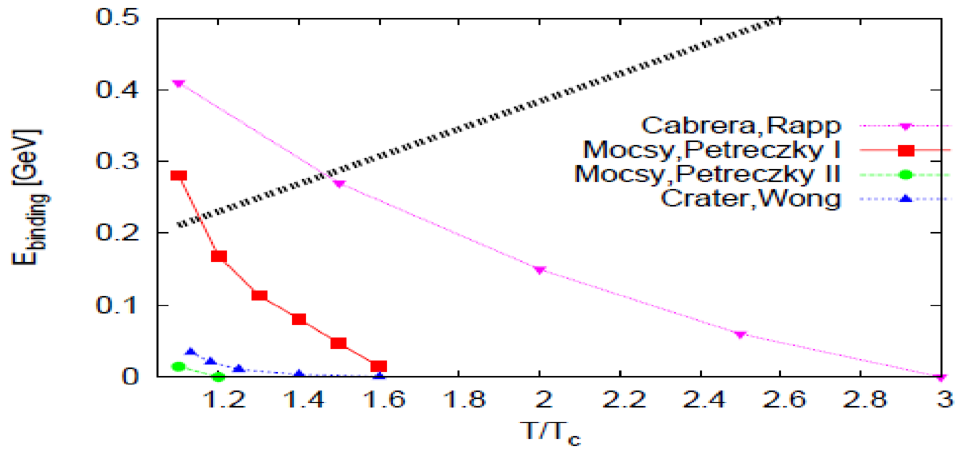
  Bottomonium
- Summary, and a few open questions

Disclaimer : not a review! Focus on ‘FASTSUM’ results for bottomonium

$$\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$$

Quarkonia in the QGP and Heavy Quark Potential

Dissociation criterium from early studies : $E_{binding}$ < T



J/ψ results

From A. Mocsy

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

Dissociation temperatures
In unit of Tc

From H. Satz

Modern era of potential studies: thermal width expressed by an imaginary component

M.Laine et al. 2006 2007 HtPT
N.Brambilla et al. 2008-2011 EFT

Same as before

From perturbation theory

$$V_A = U + i\Im[V] - \frac{0.8\,\sigma}{m_Q^2 r}$$

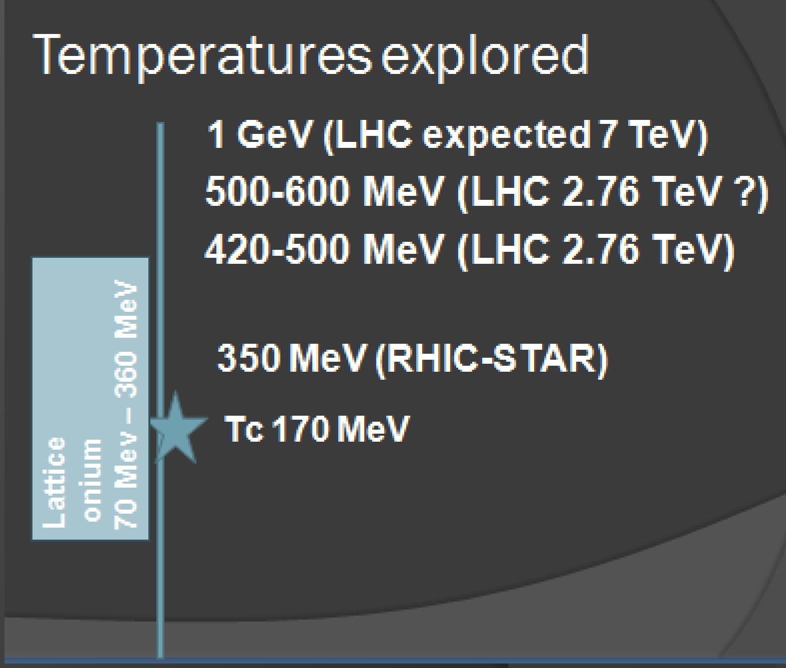
$$V_B = F + i\Im[V] - \frac{0.8\,\sigma}{m_Q^2 r}$$

+ anisotropy of the medium taken into account

M. Strickland 2012

More sound criterium for dissociation, results still ambiguous

	Isotropic		Anisotropic	
State	Potential A	Potential B	Potential A	Potential B
$\Upsilon(1s)$	298 MeV	593 MeV	373 MeV	735 MeV
$\Upsilon(2s)$	$<$ 192 MeV	228 MeV	$<$ 192 MeV	290 MeV
$\Upsilon(3s)$	$<$ 192 MeV	$<$ 192 MeV	$<$ 192 MeV	$<$ 192 MeV
χ_{b1}	$<$ 192 MeV	265 MeV	$<$ 192 MeV	351 MeV
χ_{b2}	$<$ 192 MeV	$<$ 192 MeV	$<$ 192 MeV	213 MeV



Charmonium

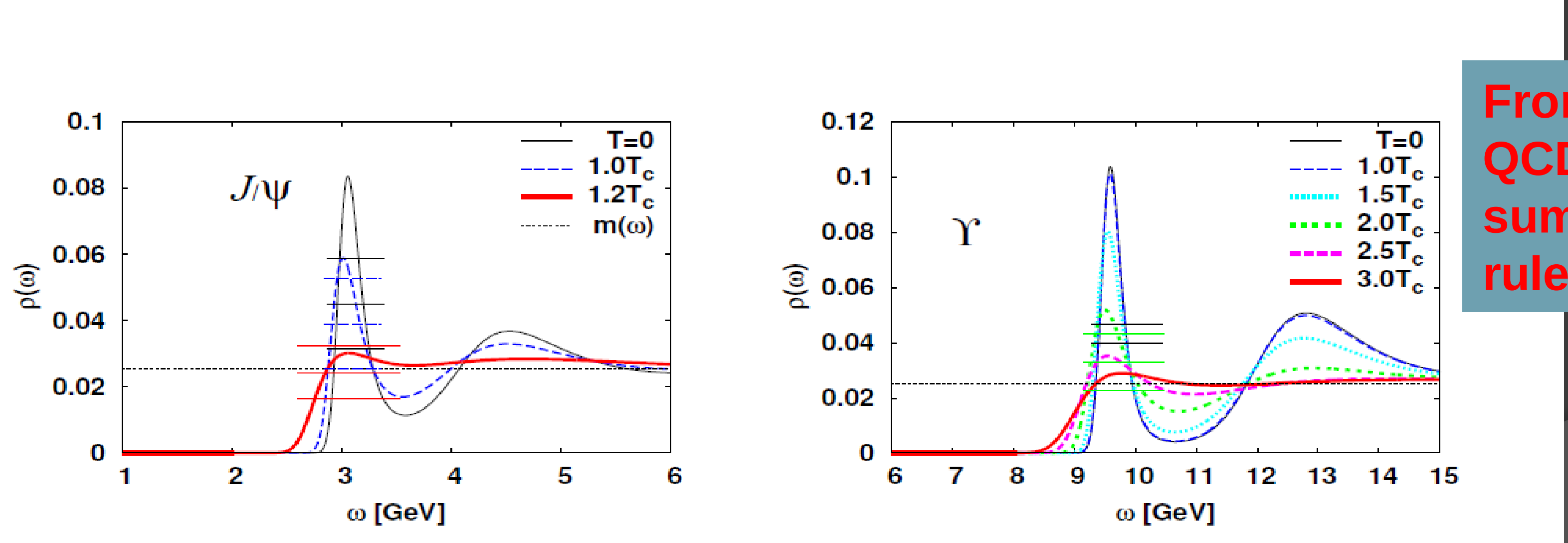
Bottomonium

Quarkonia in the QGP from first principles

$$G_i(\tau,T) = \int d\omega \; \sigma_i(\omega,T) \; K(\omega,\tau,T)$$

Spectral functions

- Full physical information
- Directly related to transport coefficients
- Difficult to compute: needs many time slices



From QCD sum rules

K.Morita 2012

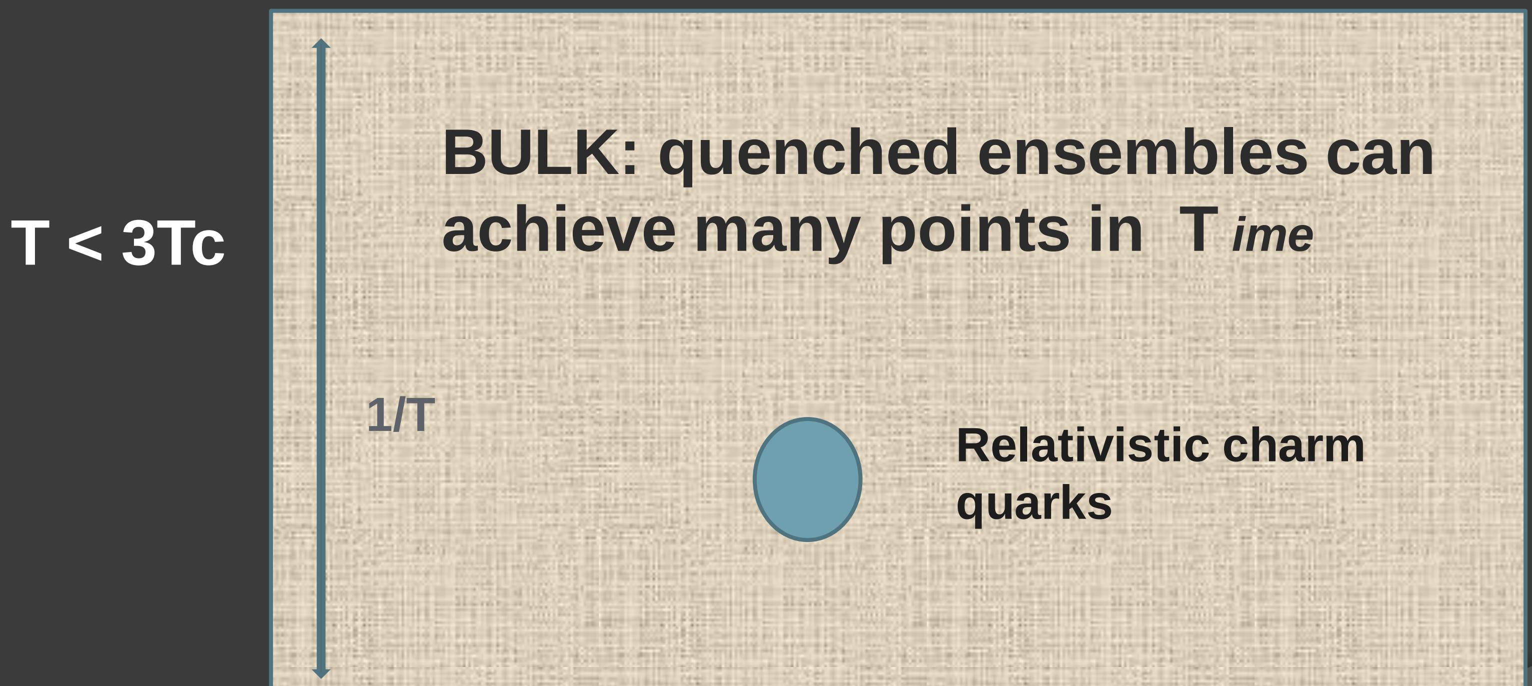
On the lattice

- Compute correlation functions on ensemble of gauge fields
- Two decisions to be made when designing a lattice ‘experimentsì

1- How to generate the configs (matter content, size, coupling...)

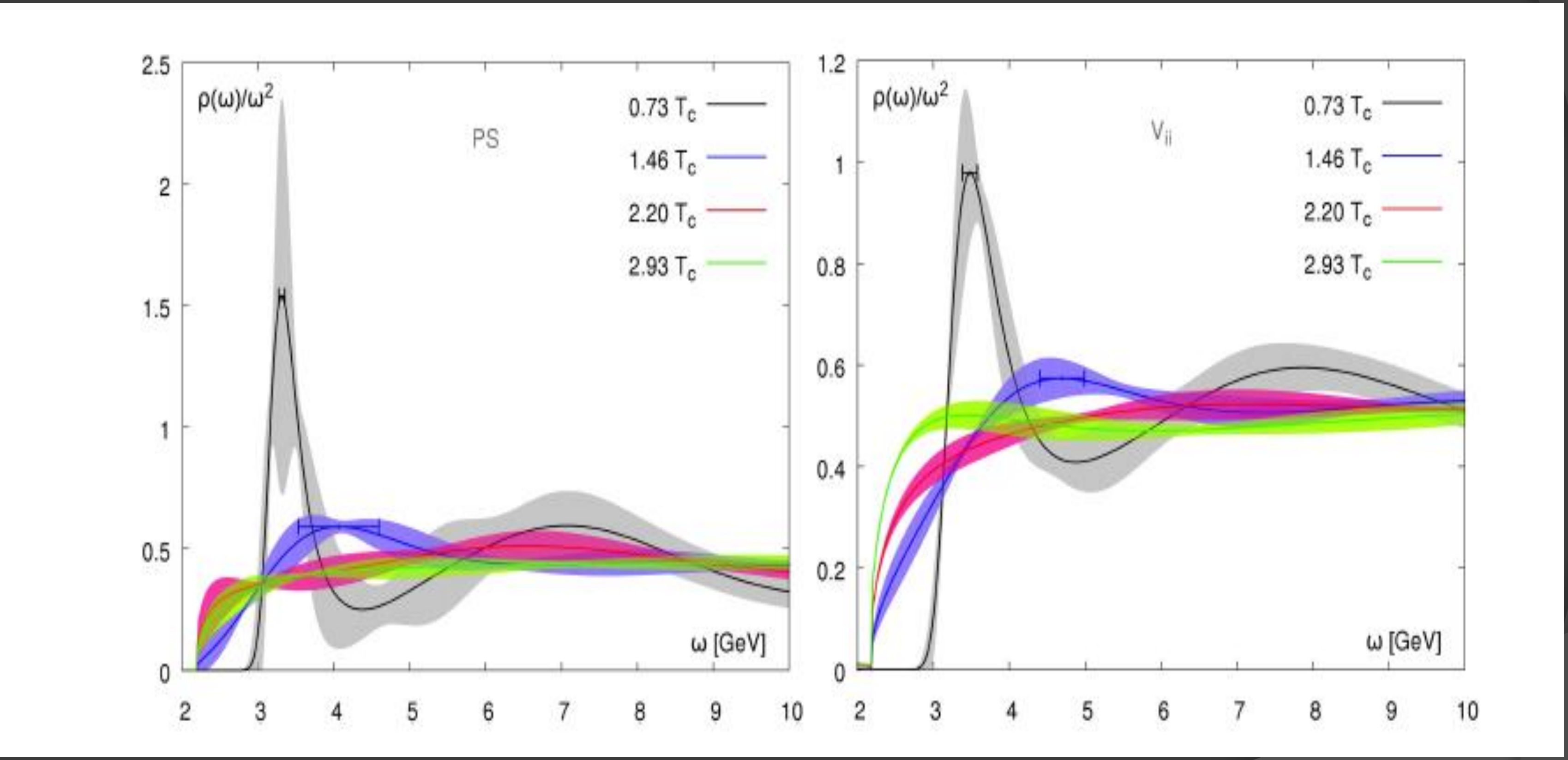
2- How to compute the correlators

Quenched approach to Charmonium



Charmonium

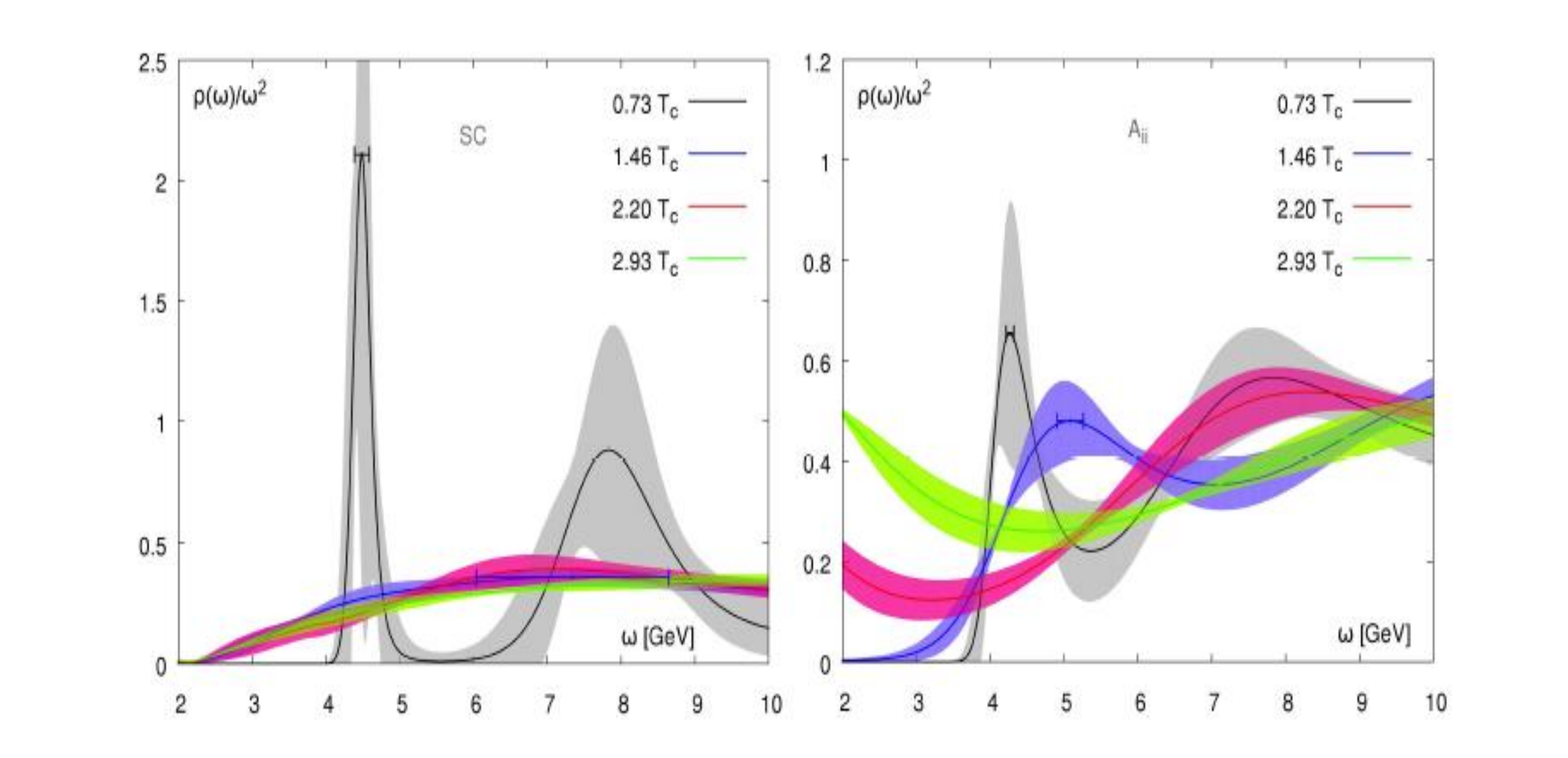
Ding et al.2012



Quenched calculation

Charmonium

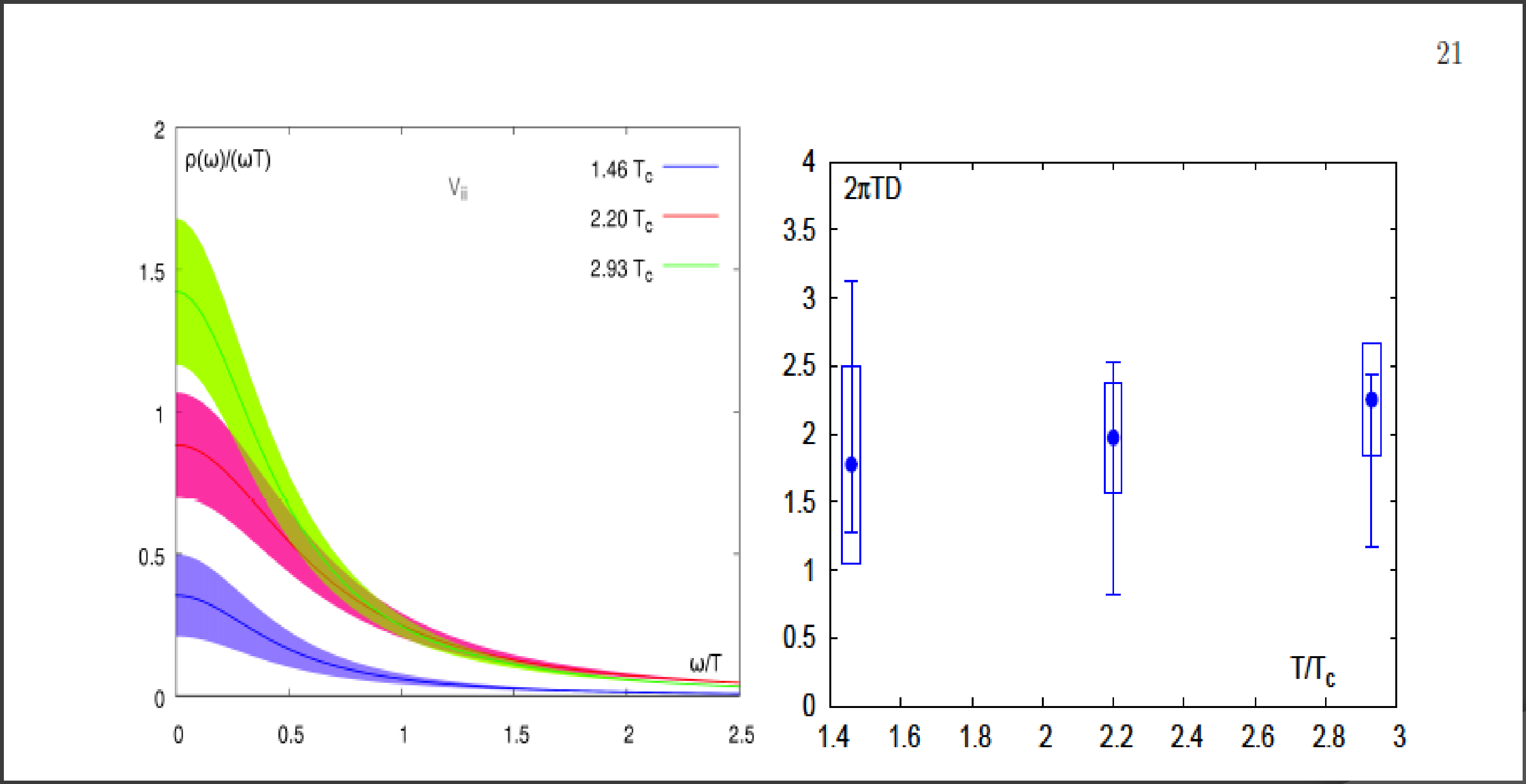
Ding et al 2012



Quenched calculation

Transport peak

Ding et al.2012



Quenched calculation

Relativistic approach to Charmonium

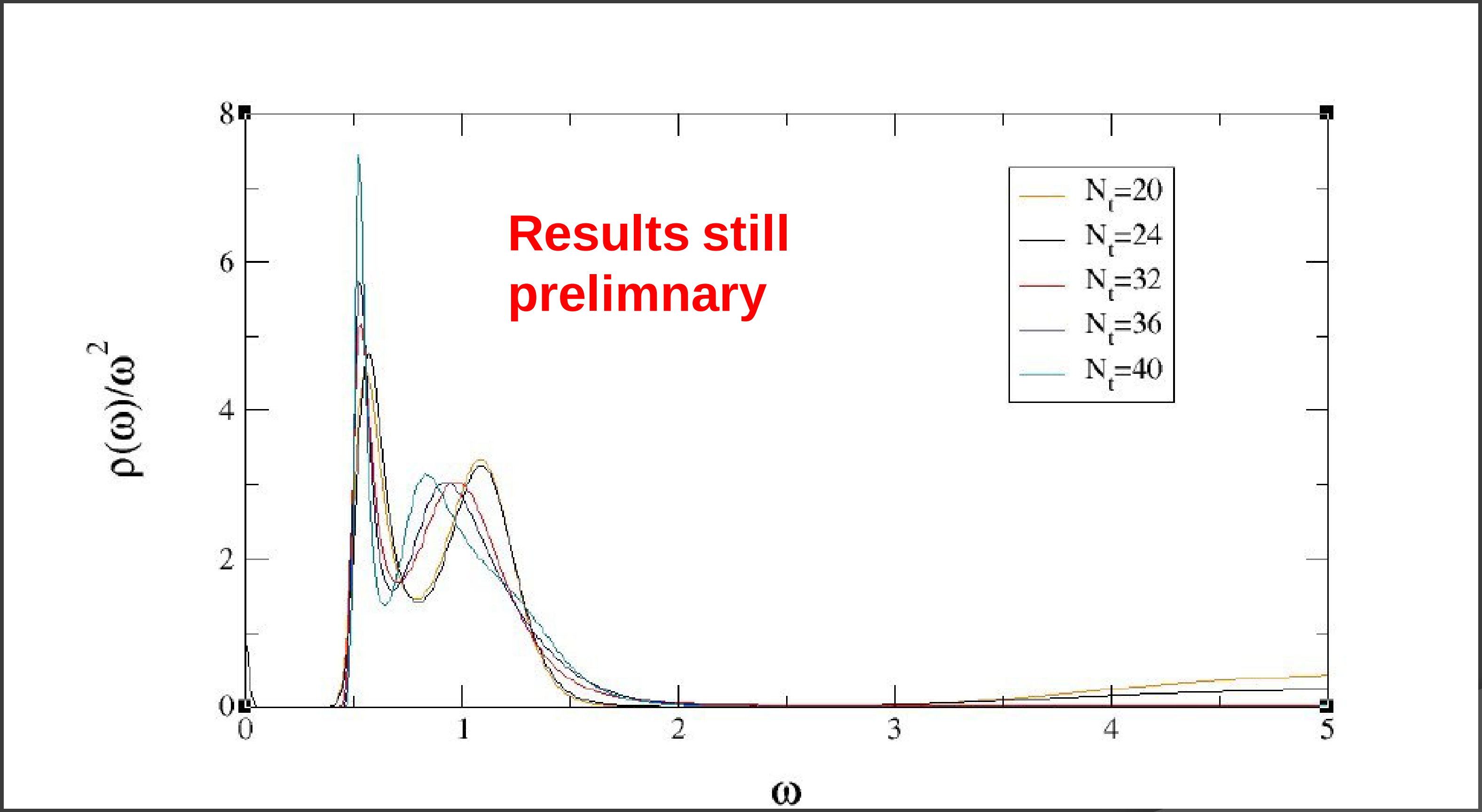
T < 2Tc

BULK: relativistic ensembles on anisotropic lattices can achieve many points in T *ime*

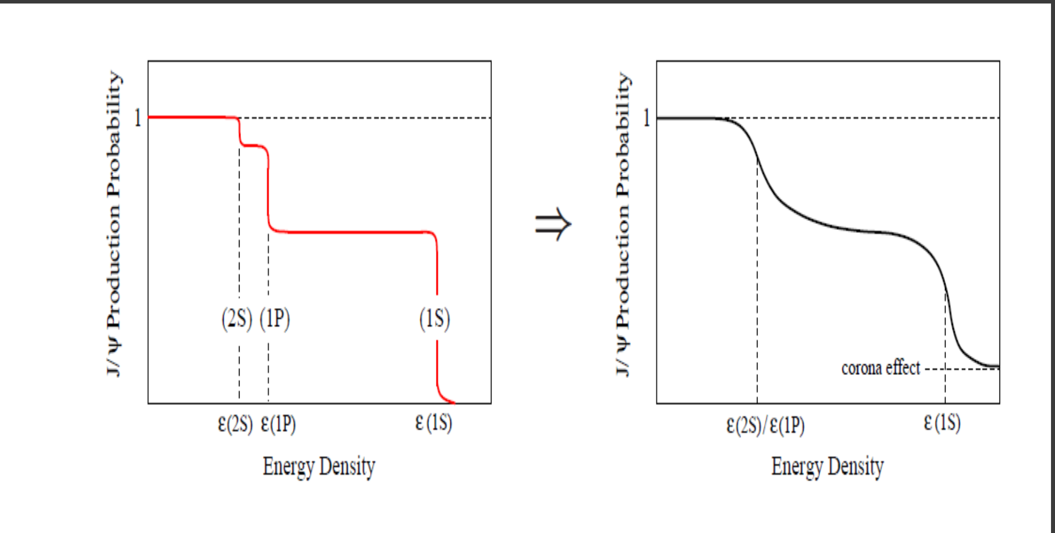
1/T

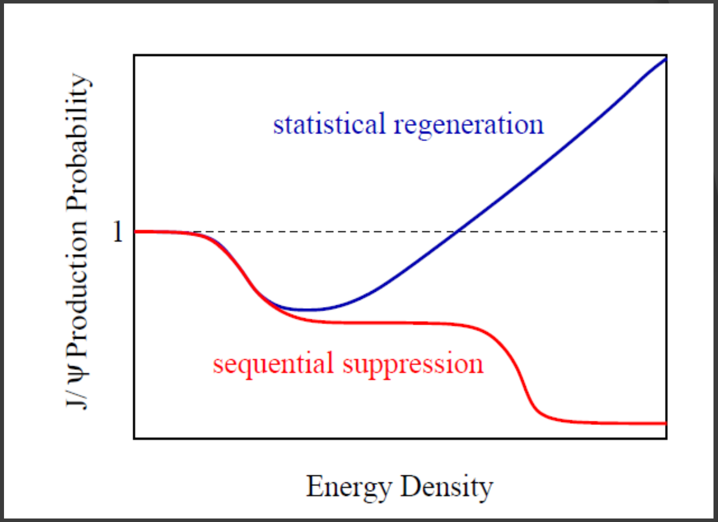
Relativistic charm quarks

Charmonium and dynamical light quarks



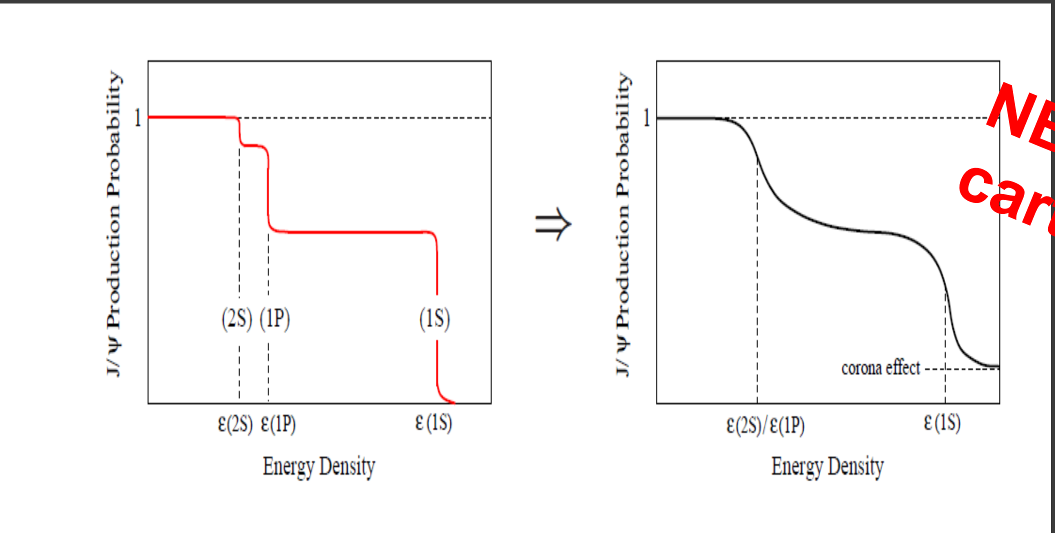
From spectral functions to sequential suppression: charmonium





From H. Satz

From spectral functions to sequential suppression: bottomonium



NB : just a cartoon!!

Bottomonium less affected by statistical regeneration ?

Hybrid approach to Bottomonium

T < 2Tc

BULK: relativistic light quarks
On highly anisotropic lattices
(many points in T directions)

1/T

NRQCD for bottom quarks:
Only forward propagation

Bottomonium

Aarts et al (FASTSUM) 2010-2013-→

- 1. Use full relativistic dynamics for up and down quarks (strange (and charm?) in progress)
- 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
- 6. Momentum and mass dependence

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	$T(\text{MeV})$	T/T_c	N_{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

$$\omega = 2M + \omega'$$ $$M \gg T$$

Scales

$$M \gg M\alpha_s \gg T \sim M\alpha_s^2$$

$M_S \sim 9.5$ GeV 400 MeV $0.2 \lesssim \alpha_s(T) \lesssim 0.4$

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

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

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

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

Laine et al 2010

Υ *and* χ_b *in the plasma* :RESULTS

Bound states

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

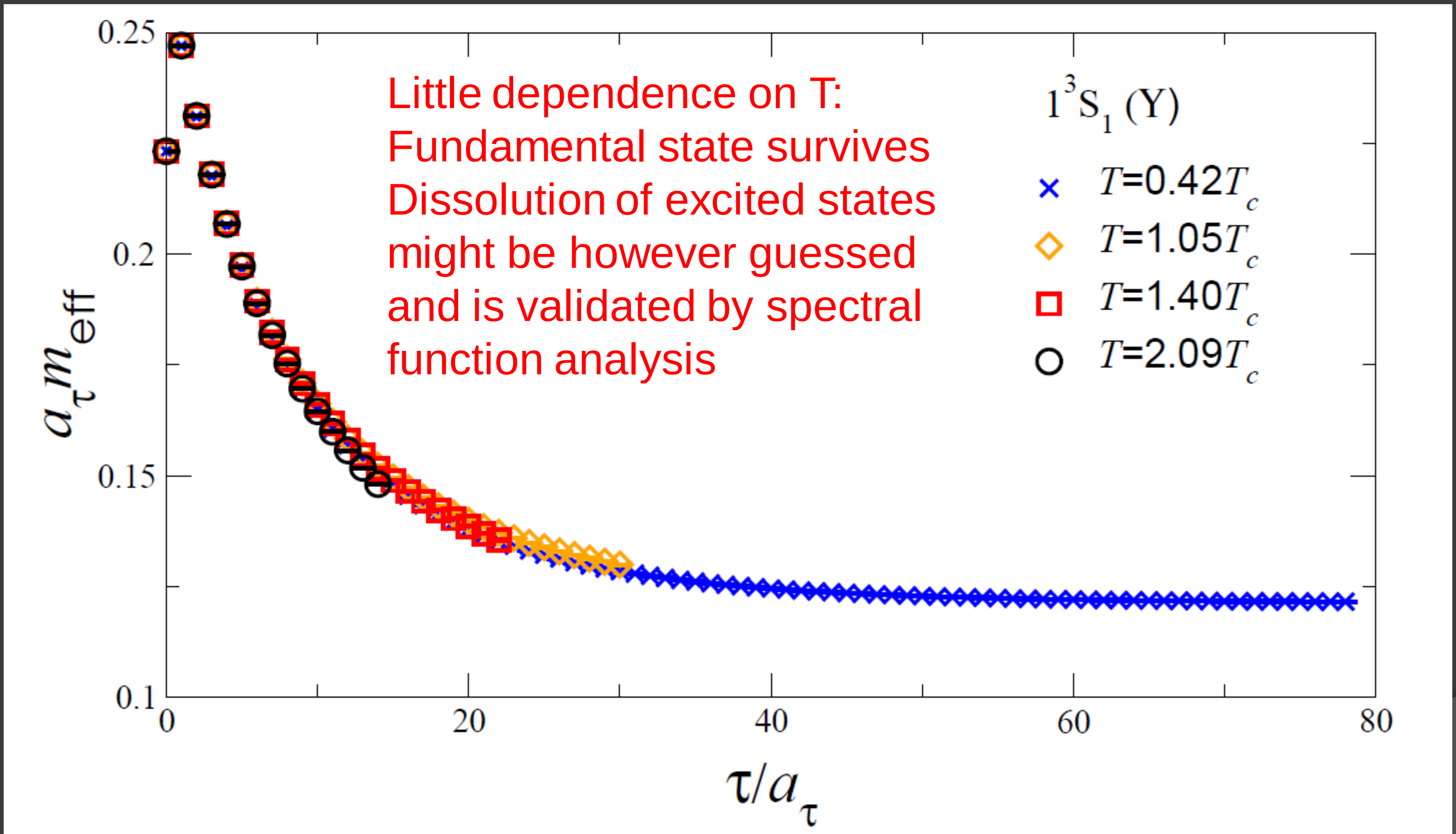
$$m_{\rm eff}(\tau) = -\log[G(\tau)/G(\tau - a_\tau)],$$

Free quarks

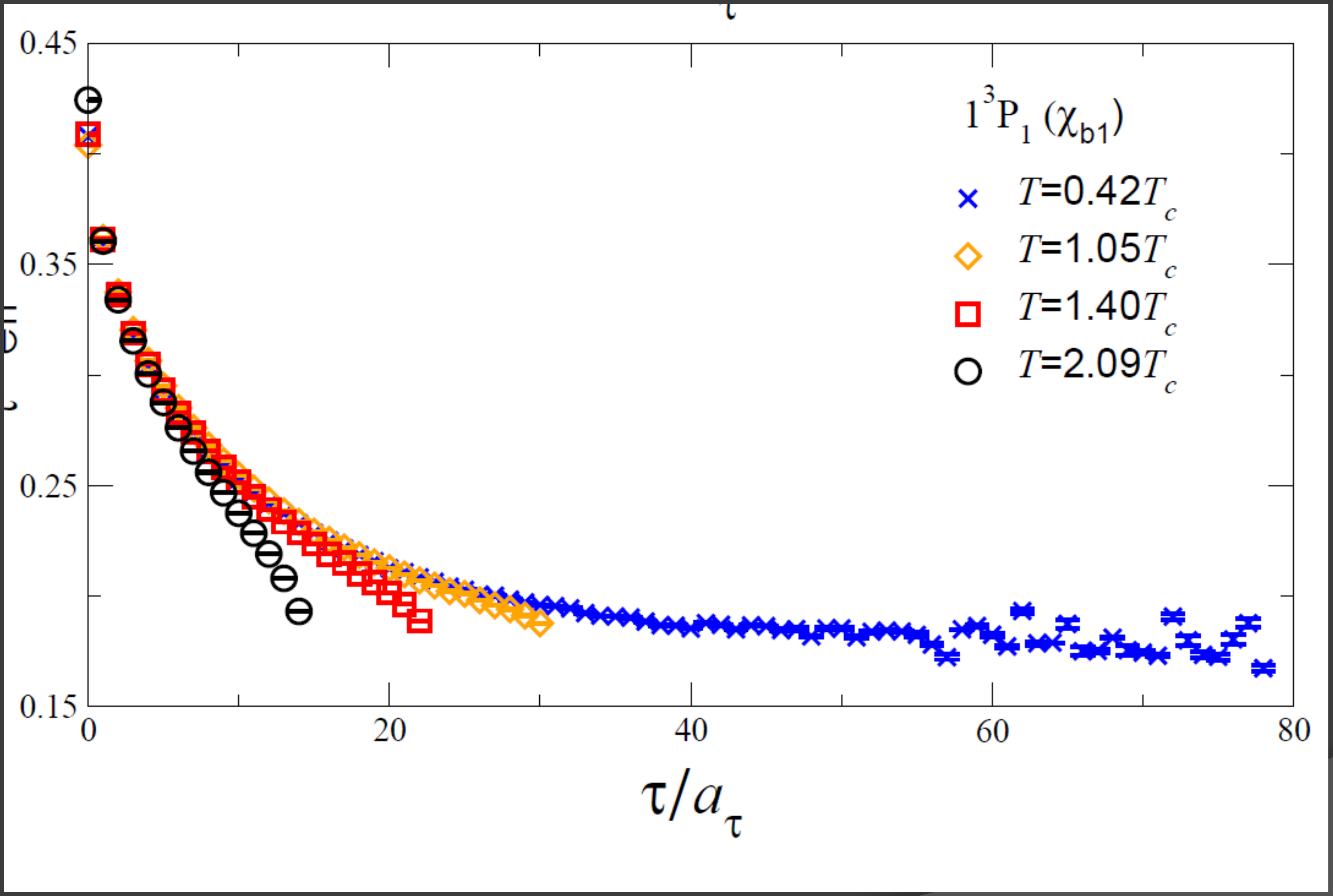
$$G(\tau) \sim \tau^{-\gamma}$$

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

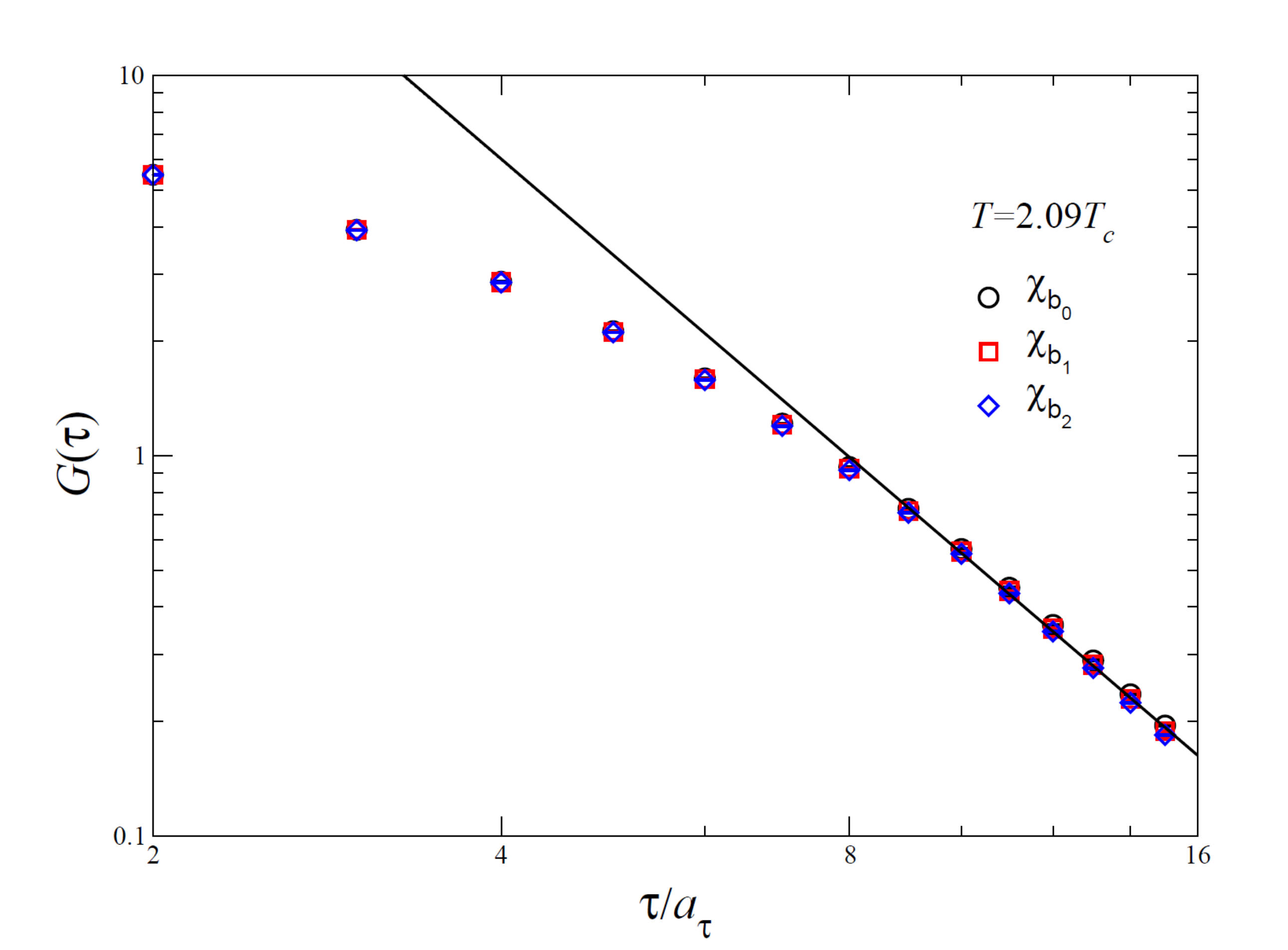
Effective mass for the Υ



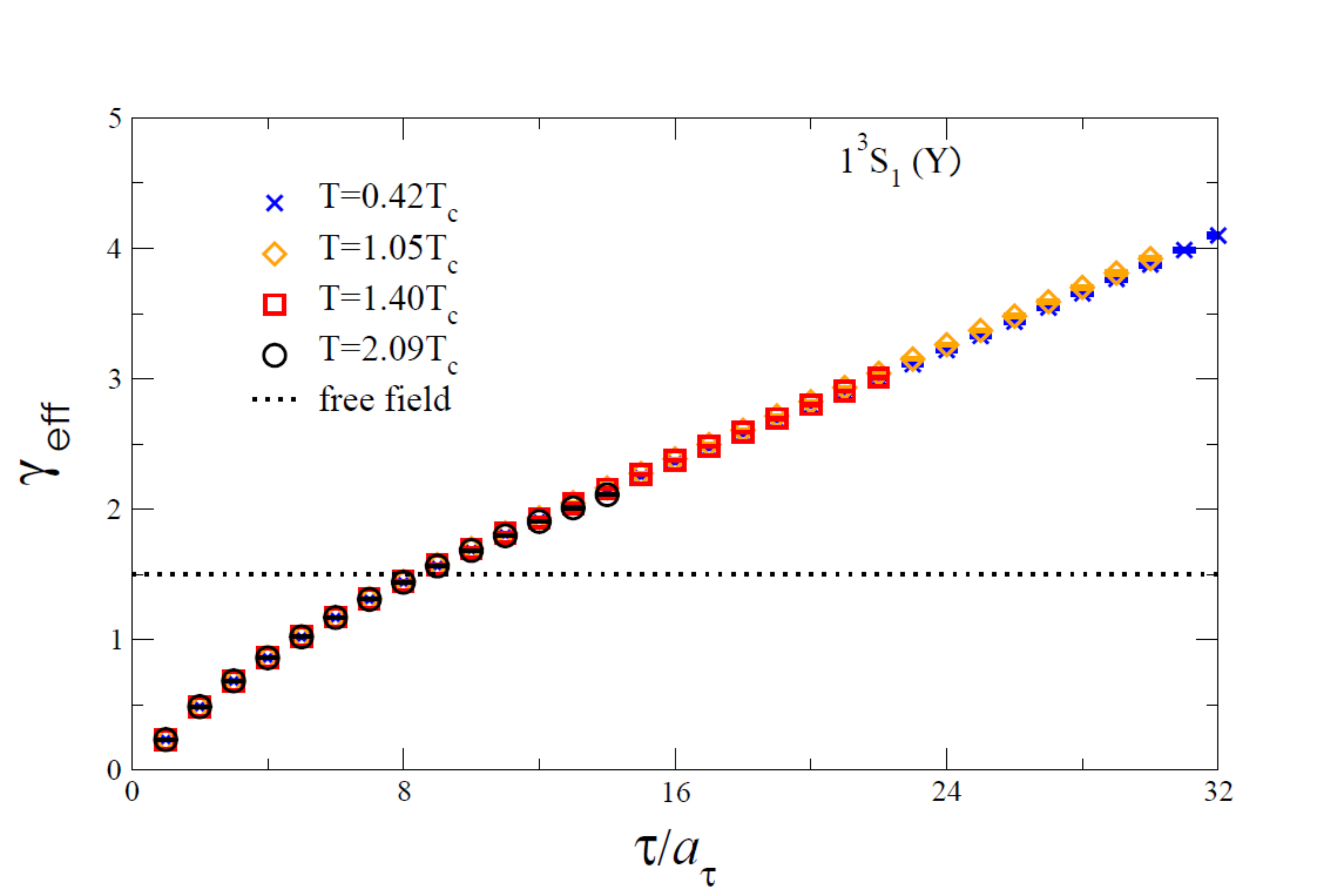
Effective mass for the χ



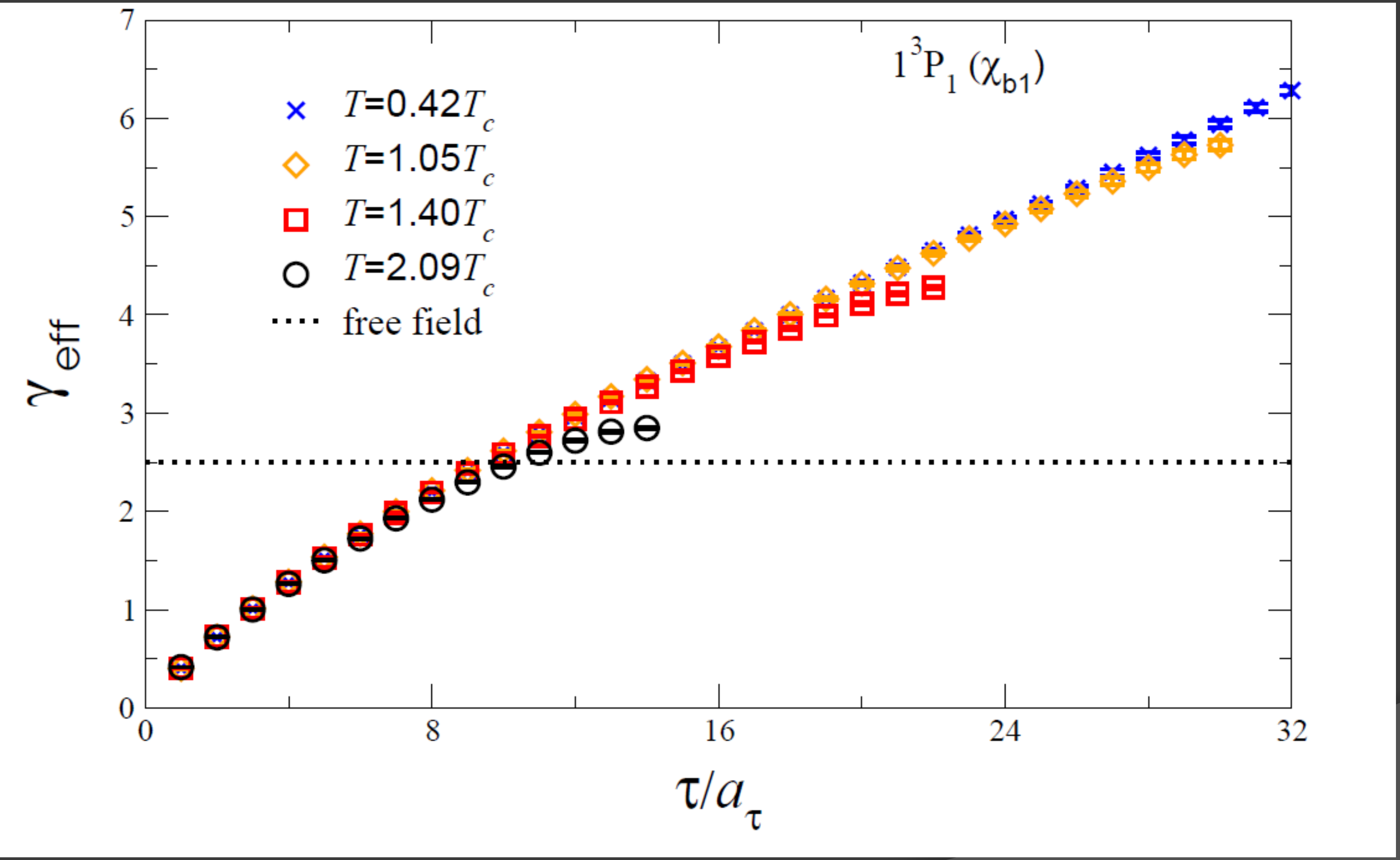
χ propagators and power law at T = 2.09 Tc : consistent with a free behaviour!



Υ 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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Laine, Petreckzy et al.

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

Spectral Functions

NRQCD PLUS'es:

No Temperature dependence in the kernel

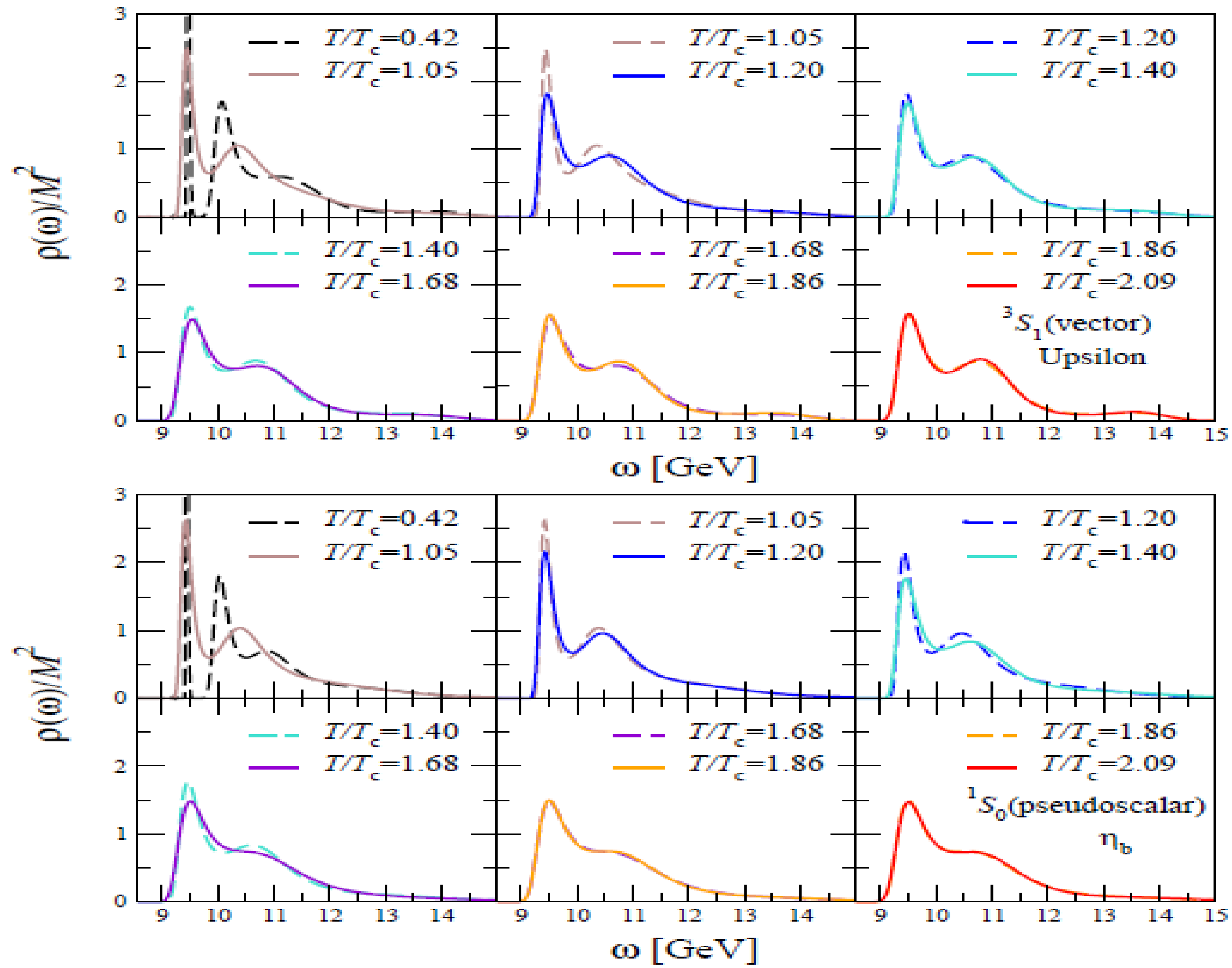
No problem with zero modes

Easier MEM analysis – *Or, perhaps, inverse Laplace transform??*

Temperature dependence of the Euclidean correlators entirely dynamical

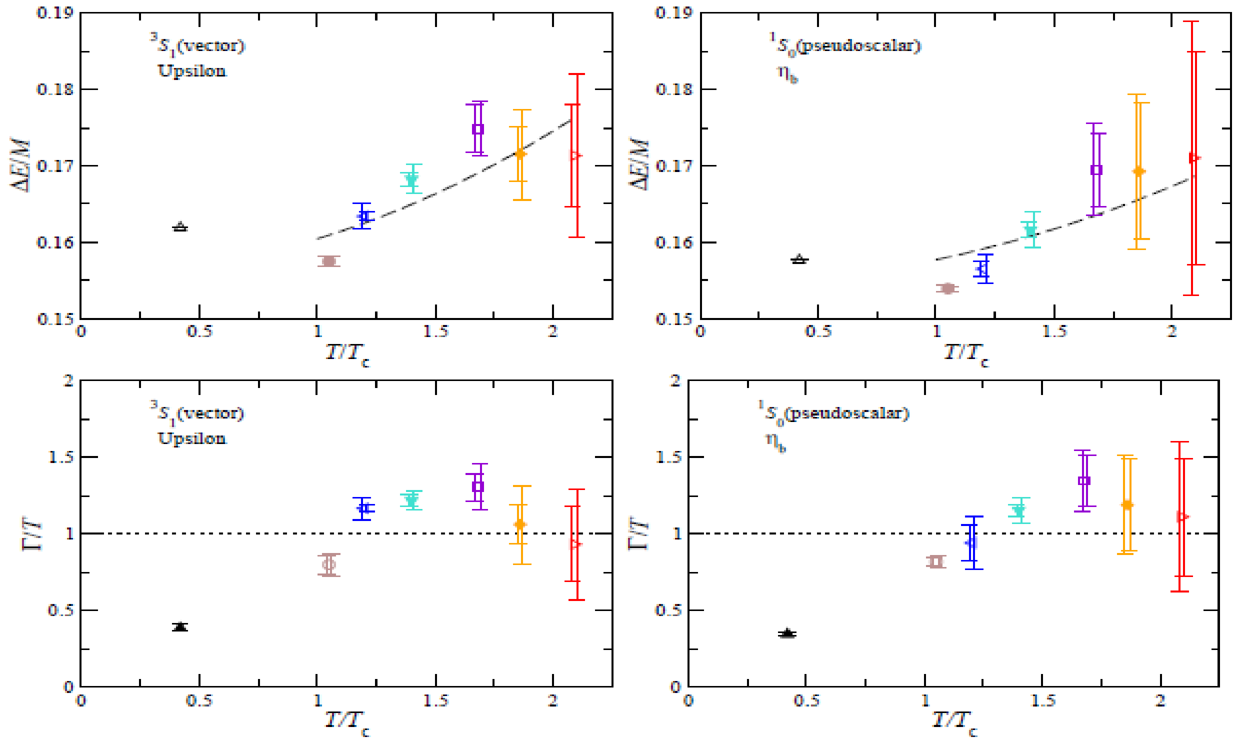
$$G(\tau) = \int_{-2M}^{\infty} \frac{d\omega'}{\pi} \exp(-\omega'\tau)\rho(\omega') \qquad \text{(NRQCD)}$$

NRQCD spectral functions – S waves melting of excited states



Step 5 : Results for Masses and Widths

S-Waves



Dashed line : fit motivated by **Brambilla et al 2010**

Comparision with EFT

[Brambilla et al.2010]

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

→

$$\alpha_s \sim 0.4,$$

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

Should be applicable when
Eb < T < 1/RB

Fit to:

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

Moving NRQCD

Lattice dispersion relations:

$$a_s^2 \mathrm{p}^2 = 4 \sum_{i=1}^{3} \sin^2 \frac{p_i}{2}, \qquad p_i = \frac{2\pi n_i}{N_s}, \qquad -\frac{N_s}{2} < n_i \leq \frac{N_s}{2}.$$

Used in this study:

$\mathbf{n}$	(1,0,0)	(1,1,0)	(1,1,1)	(2,0,0)	(2,1,0)	(2,1,1)	(2,2,0)
$\lvert\mathbf{p}\rvert$ (GeV)	0.634	0.900	1.10	1.23	1.38	1.52	1.73
v/c (Υ)	0.0670	0.0951	0.116	0.130	0.146	0.161	0.183
v/c (η_b)	0.0672	0.0954	0.117	0.130	0.146	0.161	0.183

At the largest momentum (2,2,0):

$$|\mathbf{p}| \lesssim 1.73\,\mathrm{GeV}, \qquad v = \frac{|\mathbf{p}|}{M_S} \lesssim 0.2,$$

Still non relativistic

Temperature and momentum dependence for the Y

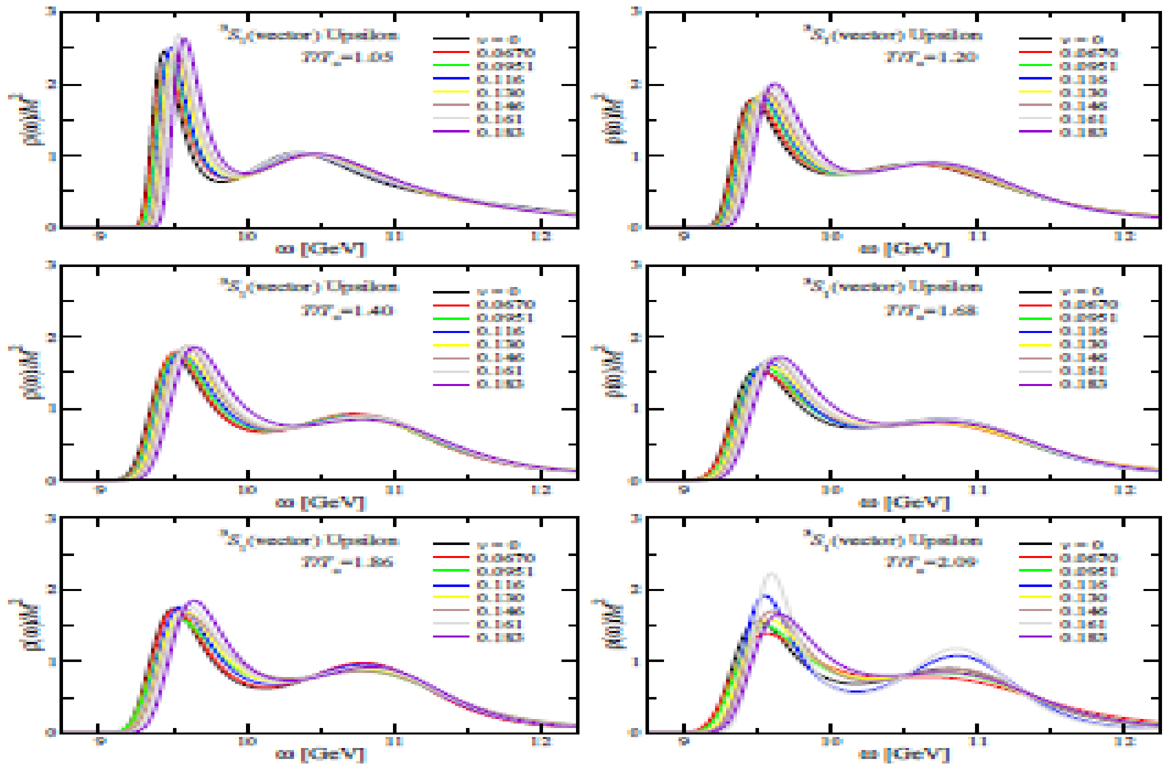
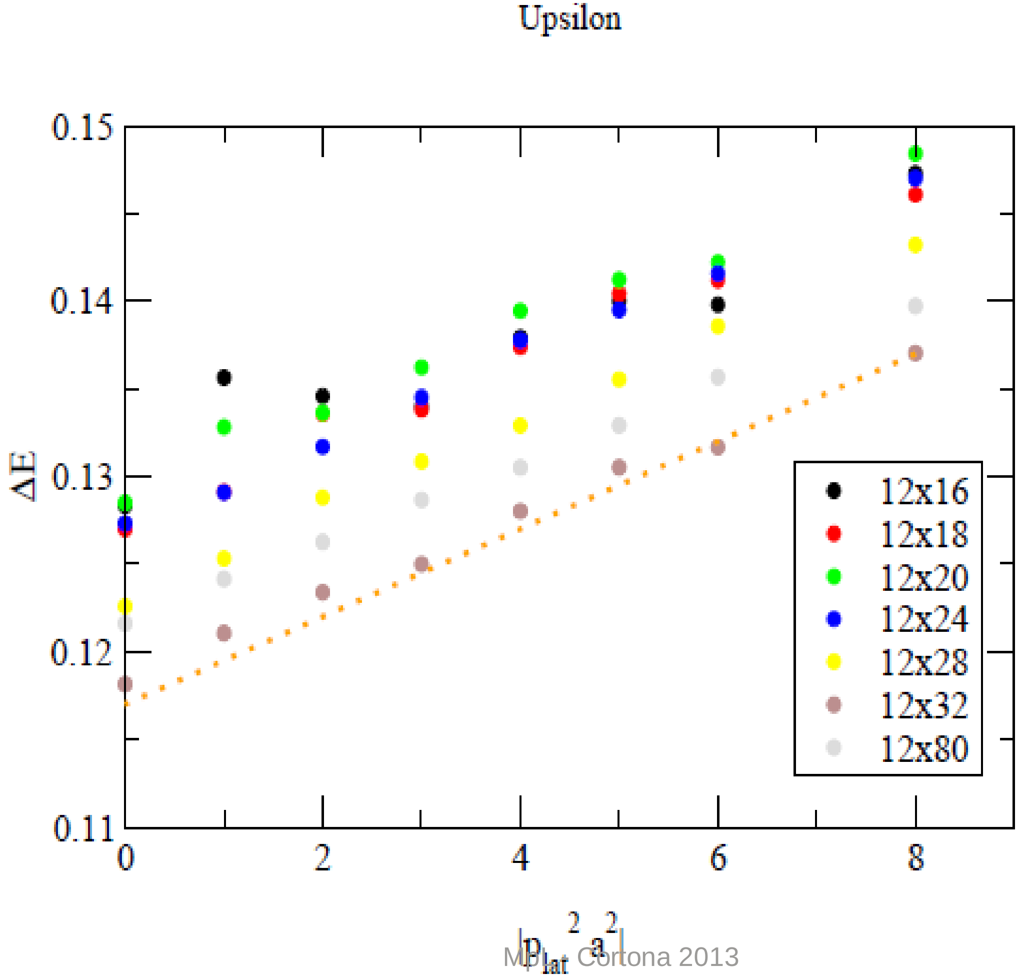


Figure 5: High-temperature results in the vector (Υ) channel. Spectral functions $\rho(\omega, \mathbf{p})$, normalized with the heavy quark mass, as a function of energy, at the six different temperatures above T_c, for several velocities $v = |\mathbf{p}|/M_\Upsilon$. fig:rho-

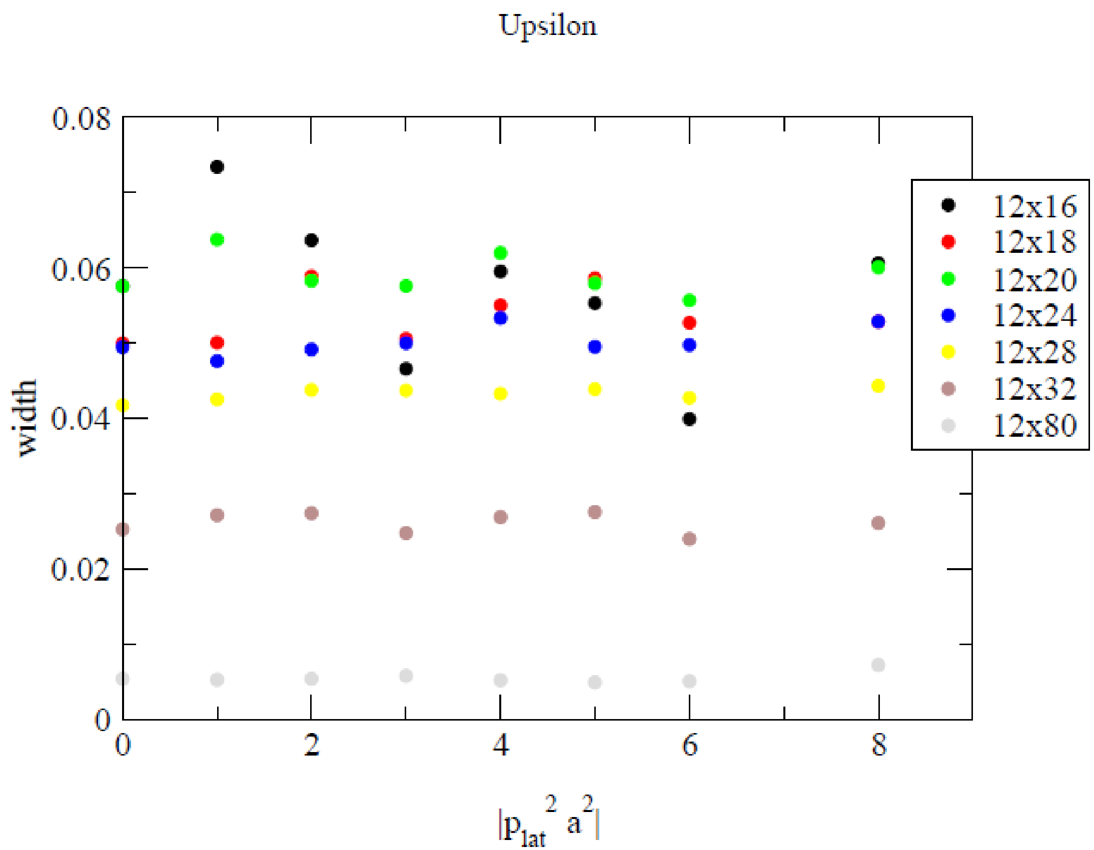
Moving Upsilon in a thermal bath: I

- observable heavy quarkonium velocity ($\frac{v^2_{\text{Upsilon}}}{c^2} \sim 0.03$) effect on the S-wave state mass (NR dispersion $\sim \frac{\vec{p}^2}{2M_{\text{Upsilon}}}$)



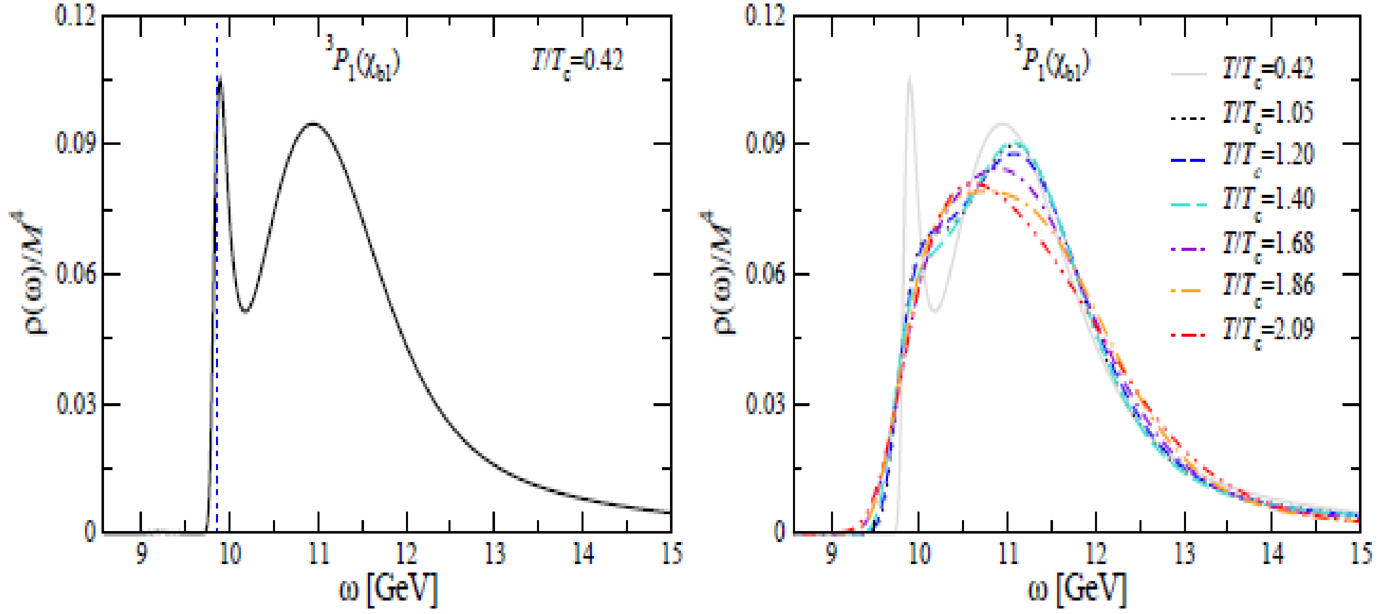
Moving Upsilon in a thermal bath: II

- no observable v^2_{Upsilon} effect on the S-wave state “width” (Escobedo et al., PRD84 (2011) 016008, $\Gamma_v/\Gamma_0 \sim 1 - \frac{2}{3}v^2_{\mathrm{Upsilon}}$)

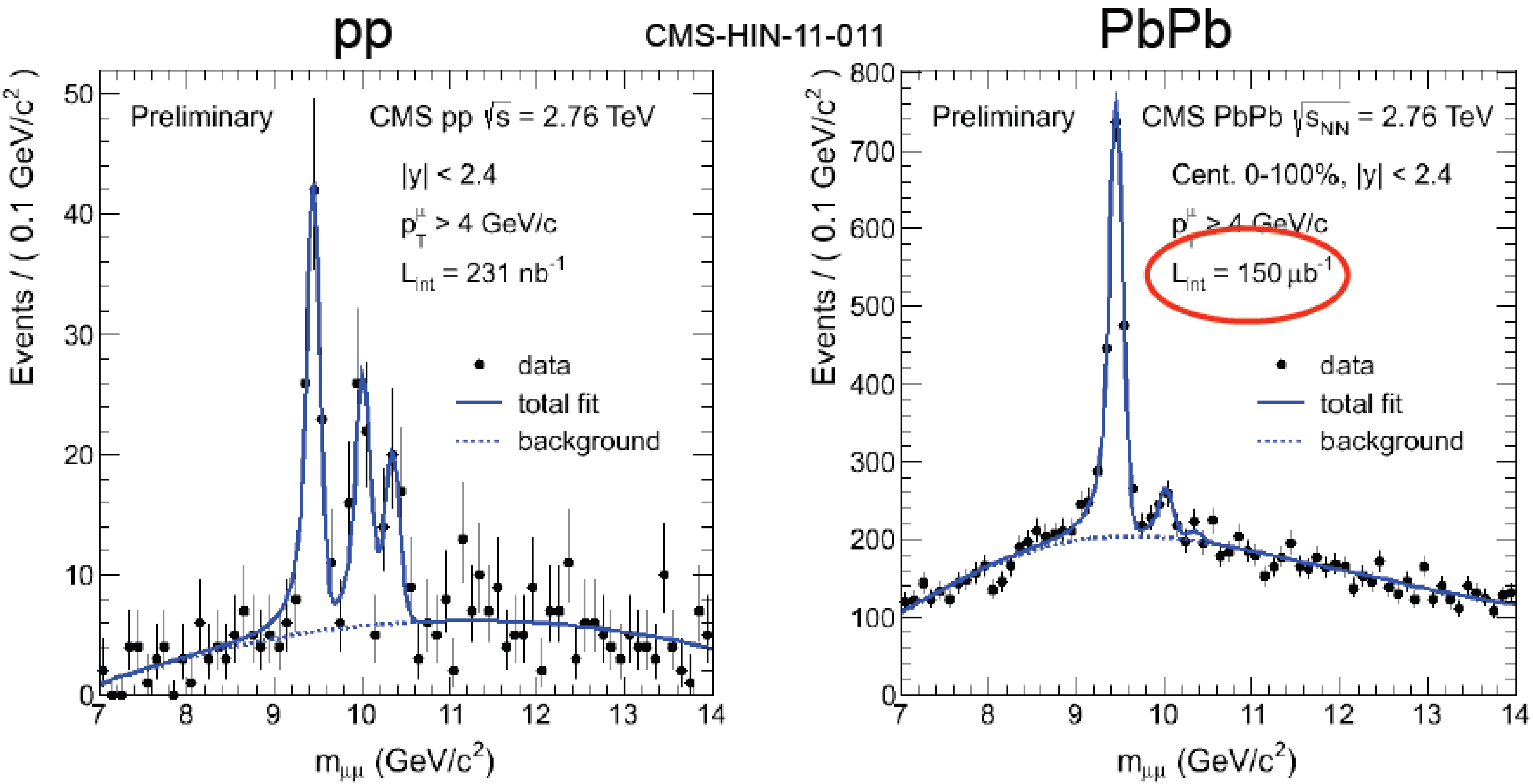


Slide from
S Kim
@Lat2012

Melting of P-waves from the spectral functions



Bottomonia: with 2011 data



$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

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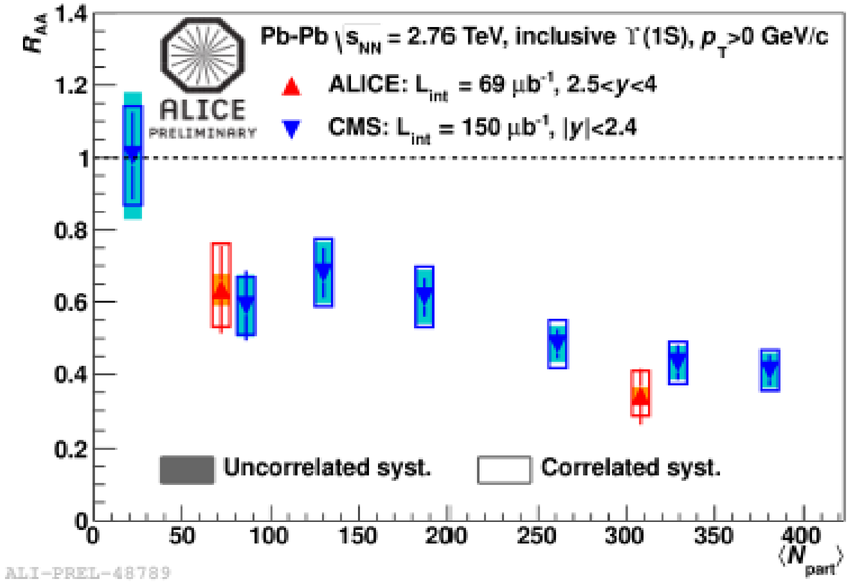
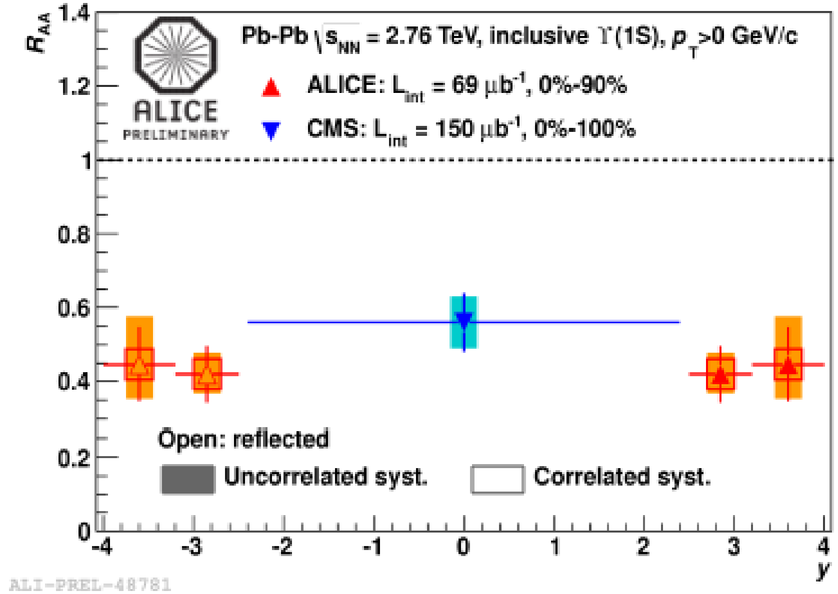
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Ratios not corrected for acceptance and efficiency

Comparison of ALICE forward-rapidity results with CMS mid-rapidity



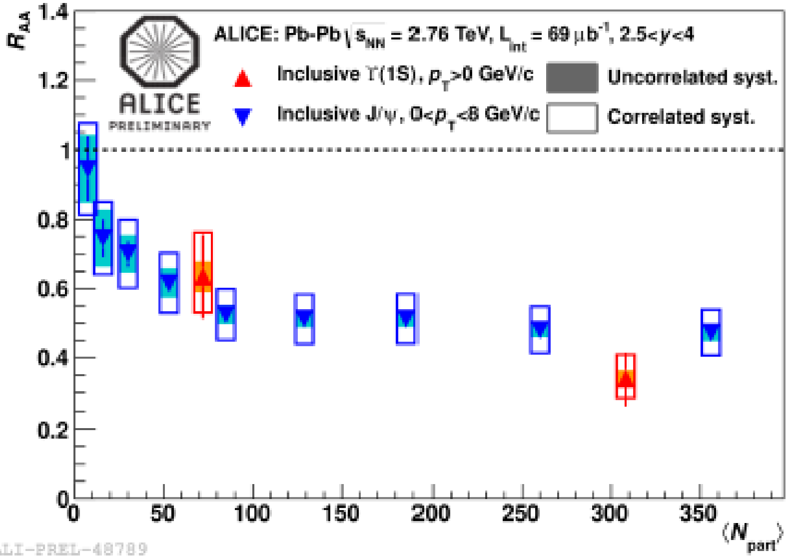


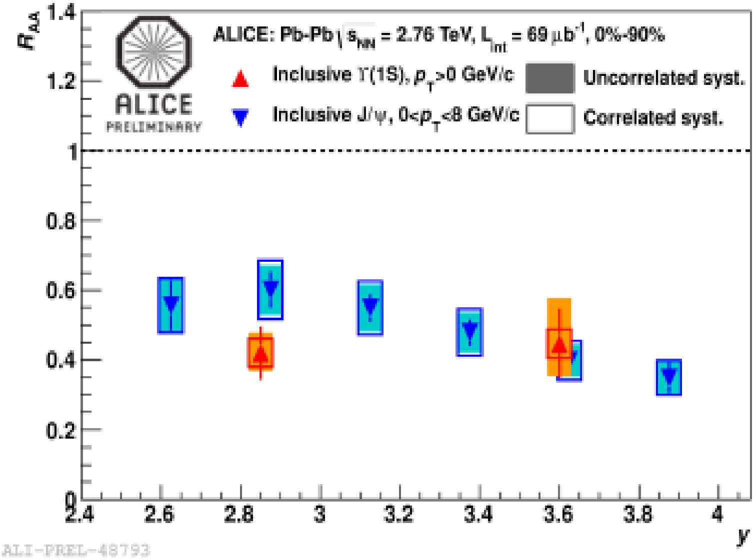
→ The suppression at forward rapidity in ALICE is similar to that at mid-rapidity measured by CMS for both central and semi-peripheral collisions

→ No strong rapidity dependence of R_{AA} within the large range probed by ALICE and CMS

Reference for CMS Data points: PRL 109, 222301, (2012)

Comparison of J/ψ and ϒ(1S)





→ Suppression of ϒ and J/ψ is comparable within the present uncertainties

→ ϒ is expected to be less sensitive to regeneration than J/ψ

→ Feed down from higher excited states ϒ(2S), ϒ(3S), χ_b, χ_b' ~ 50 %

→ Weak rapidity dependence of R_{AA} for both J/ψ and ϒ(1S)

* for J/ψ in Pb-Pb see the talk of Lizardo Valencia Palomo

Summary

- High quality results for ***charmonium*** from relativistic spectral functions with quenched gauge fields.
- Possible to extract trasport coefficient
- No signs of bound states at temperatures above **1.46 Tc**
- The temperature dependence of ***bottomonium*** for 0.4 Tc < T < T 2.1 Tc has been investigated with nonrelativistic dynamics for the bottom quark and full relativistic QCD for up and down quarks
- Correlators and spectral functions indicate that the Upsilon and ηb 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 ηb excited states are no longer visible at temperatures above **1.4 Tc** , in agreement with experimental observations at RHIC and LHC

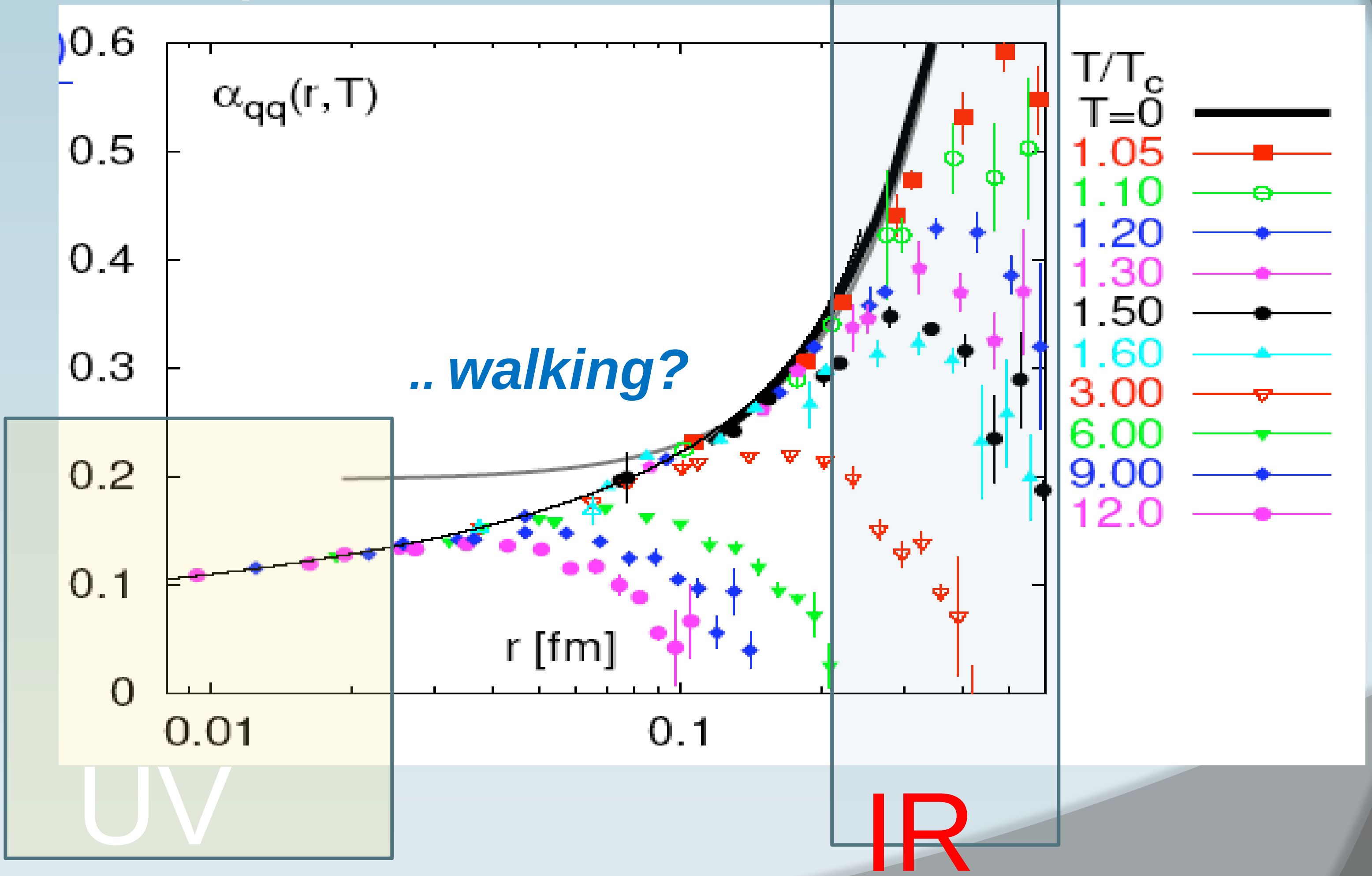
What is needed:

- Better control on spectral functions: lattice issues & general issues on methodology

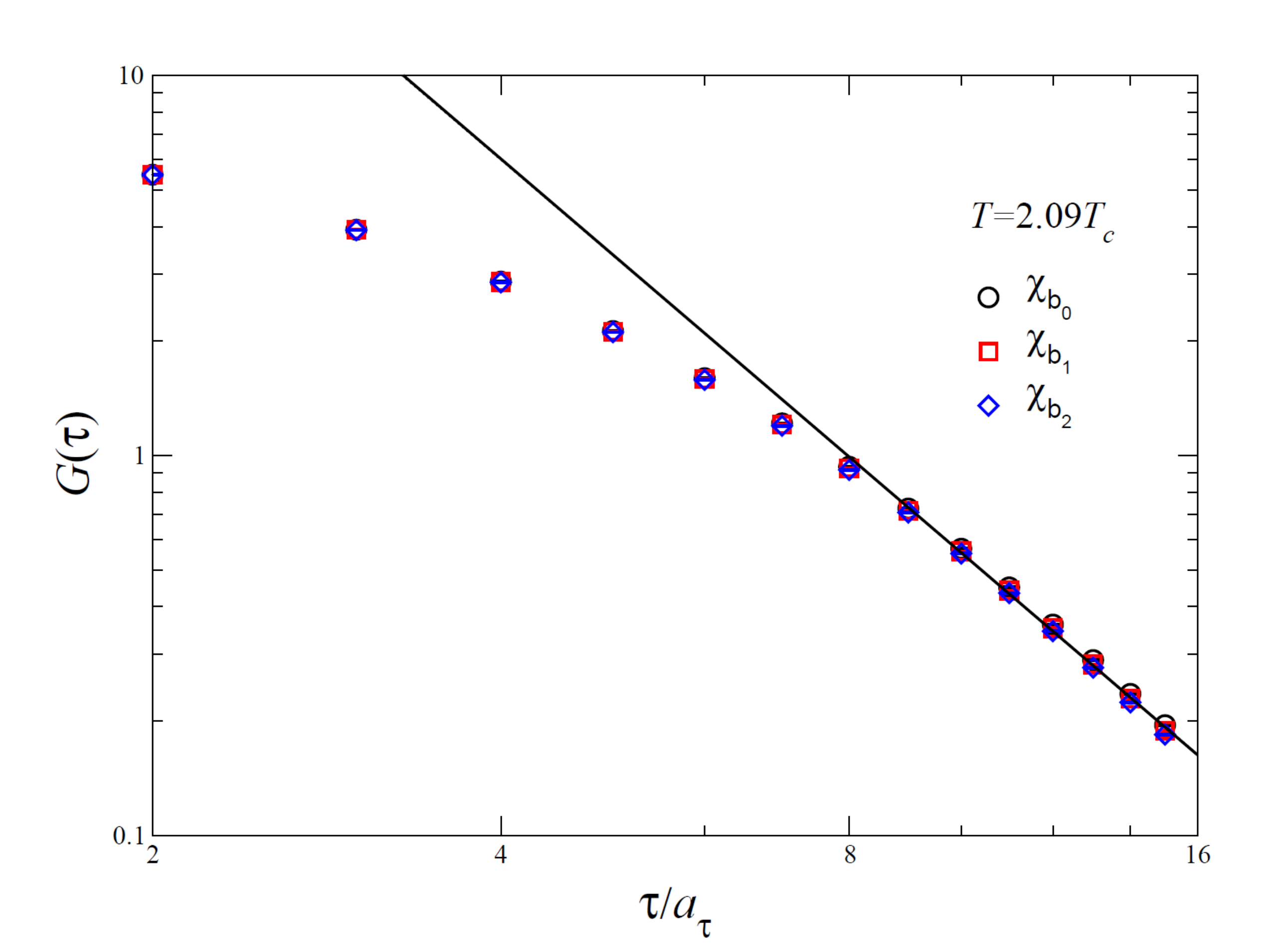
- Clear understanding of the interrelation between the experiemntal suppression and the spectral functions: model analysis, and non equilibrium dynamics

Some topics for discussions

improving on αs
-- also Nf dependence!

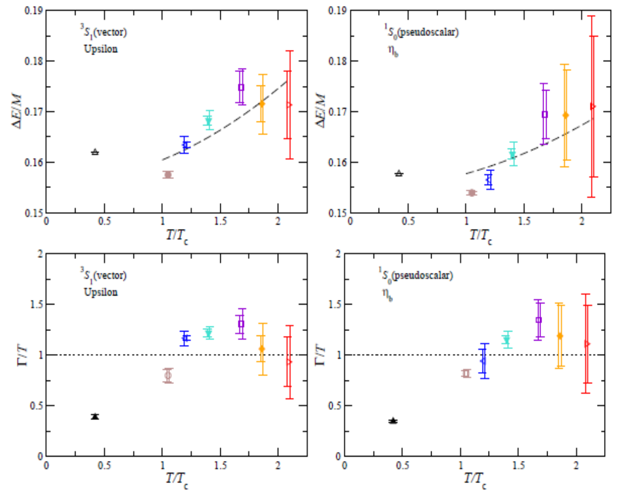


Analytic models for correlators?

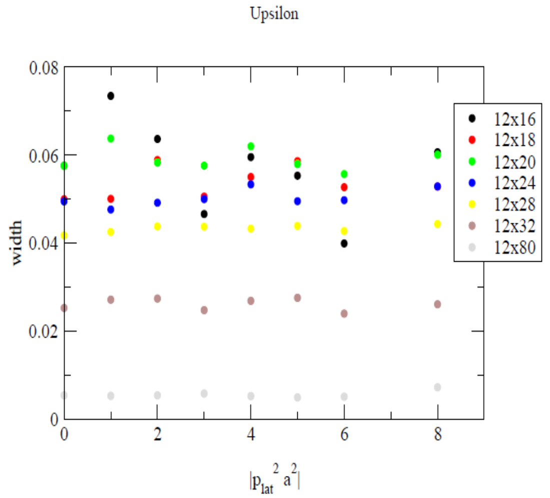


The line is Power-law like – can we find a more general form for smaller temperatures– smaller distances?

Improving on the comparison with EFT:



- no observable v^2_{Upsilon} effect on the S-wave state "width" (Escobedo et al., PRD84 (2011) 016008, $\Gamma_v/\Gamma_0 \sim 1 - \frac{2}{3}v^2_{\text{Upsilon}}$)

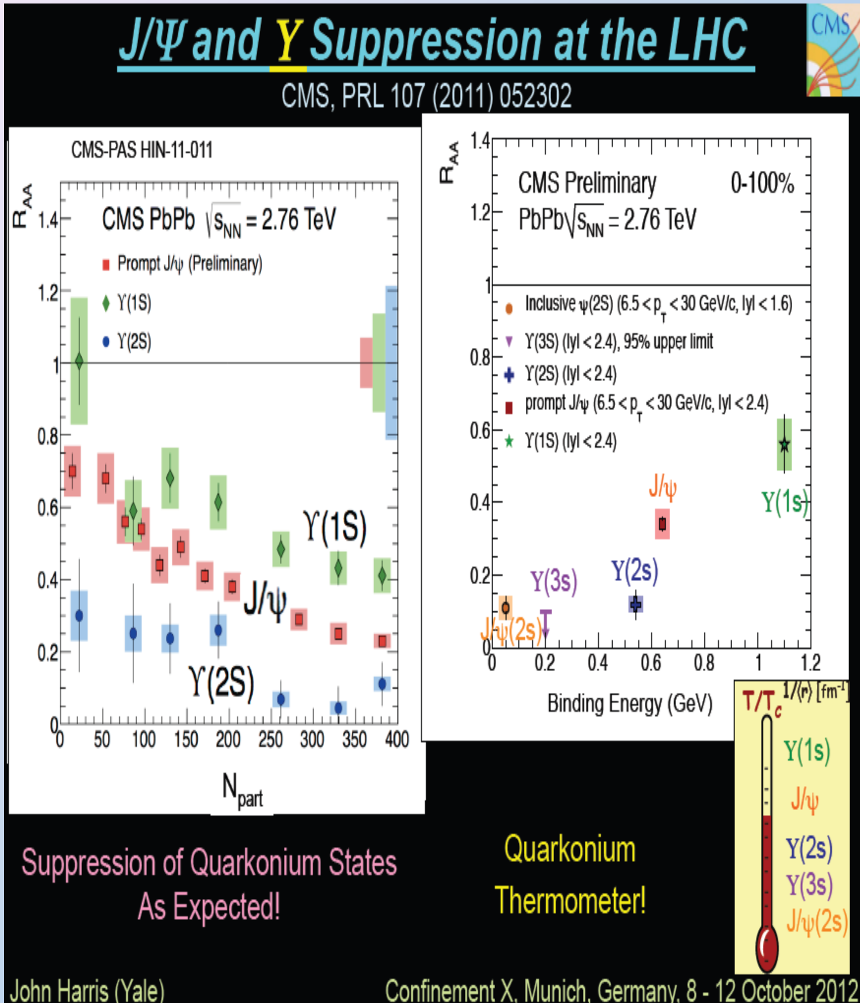


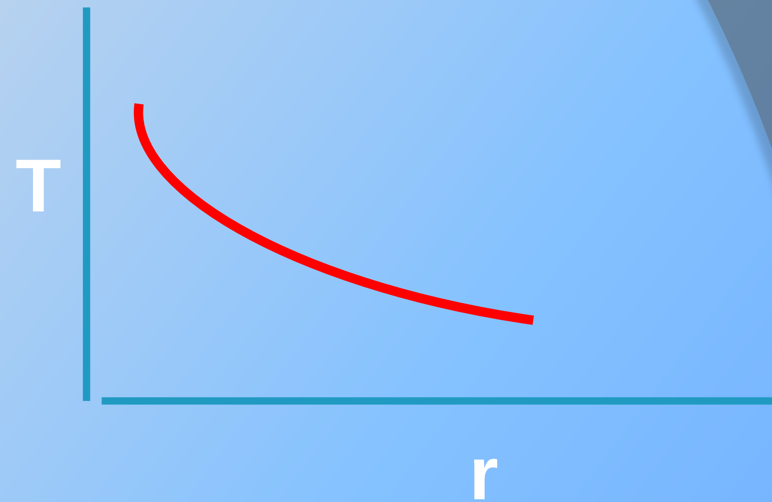
2S state?
Bc states?
Fictitious mesons with a variable mass?

Worth extending the momentum range?

Finding a better temperature,mass setup for study of momentum dependence?

Can we draw a ‘pseudocritical line’ for melting ? Or,rather, a surface??





Quarkonia: heavy quarks ⇒ non-relativistic potential theory

Jacobs et al. 1986

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

with confining (“Cornell”) potential $V(r) = \sigma\, r - \frac{\alpha}{r}$

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

4