Quarkonia in relativistic heavy ion collisions

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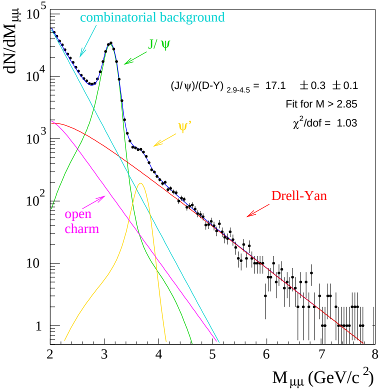
Introduction

Quarkonia: $Q\bar{Q}$ mesons where $Q = b, c$

Theorists love them.
Theoretically simpler.
$m_Q \gg \Lambda_{QCD}$
Production in hard collisions.
Approximately nonrelativistic.

Experimentalists love them.
Sharp peaks in dilepton channels from $J/\psi, \Upsilon(1S)$



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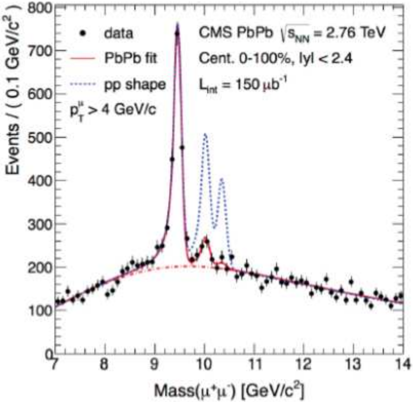
QGP hunters **really** love them.
QGP *melts* these peaks.



CMS (2012)

Quarkonia in medium

- At high temperatures, the medium will have lot of energetic gluons which can collide with the $\bar{Q}Q$ pair and break it apart.
- Assuming that $\bar{Q}Q$ not produced in medium, this will lead to a suppression of quarkonia.
- This lead to the suggestion of quarkonia as probe of creation of QGP.

T. Matsui & H. Satz, 1986

- Work with a Debye-screened potential lead to a pattern of sequential suppression.
- Different quarkonia have different dissociation temperatures.
- Quarkonia as thermometer of the medium.

F. Karsch and H. Satz, Z. Phys. C51, 209 (1991)
S. Digal *et al.*, Phys. Rev. D 64, 094015 (2001)

Quarkonia in relativistic heavy ion collision

- Fixed target Pb-Pb collisions at 158 A GeV ($\sqrt{s} \sim 18$ A GeV) saw "anomalous suppression" of J/ψ, which was attributed to QGP formation.
- Data from smaller systems (e.g., In-In in SPS at 158 A GeV) can be explained without invoking QGP suppression.
- Au-Au collisions in RHIC at $\sqrt{s} = 200$ A GeV saw strong J/ψ suppression.
- Wealth of very interesting data on $J/\psi, \Upsilon(1S)$ and other quarkonia obtained from Pb-Pb collisions in LHC, leading to lots of new puzzles.
- From a "thermometer" or "marker of deconfinement", quarkonia have become a challenge, a test of our understanding of strongly interacting QGP.
- CBM provides excellent opportunity to take the study of quarkonia to a new regime.

$\bar{Q}Q$ in heavy ion collision

A proper phenomenology has to rely on answer to various questions.

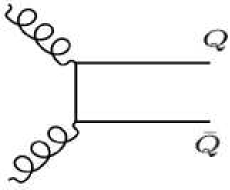
1. How is quarkonium produced in pp collisions?
2. Production in AA: same as $\bar{p}p$? Or gluon distribution functions change in-medium?
3. Interaction of the quarkonium with the thermal medium.
4. Quarkonia *regeneration* from the thermal medium?
5. Temperature variation and anisotropy of produced medium

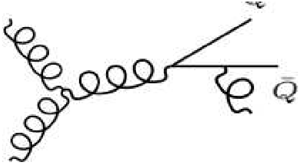
   Krouppa, Ryblewski, Strickland, PRC 92 (2015) 061901

6. Interaction of the quarkonium with the *hadronic* matter.

Production in *pp*

In LHC, $\bar{Q}Q$ will be created from collision of partons with momentum fraction x: $0.6 - 6 \times 10^{-3}$ for J/ψ and $2 - 20 \times 10^{-3}$ for $\Upsilon(1S)$ at $\sqrt{s} = 5$ TeV.





NRQCD suggests the second diagram dominates: $\bar{Q}Q$ produced predominantly in color octet configuration, emits soft gluon to create quarkonia at time τ_f ($\sim$ 0.4 fm for J/ψ, 0.2 fm for $\Upsilon(1S)$)
Note that while this picture explains p_T distribution excellently, it fails to explain polarization.

ALICE, PRL 108 (2012) 082001.

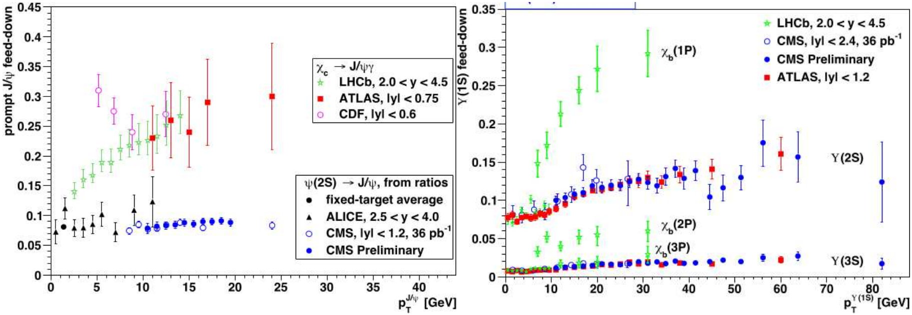
Production issues

The NRQCD picture predicts, for J/ψ at large momenta, $\gamma\tau_f >$ medium formation time. The color octet $\bar{Q}Q$ will interact vigorously with the medium.

Arleo & Peigne, 2012; Sharma & Vitev, 2009

For CBM, $x \sim 0.35 - 0.45$ so valence quarks will be important.
Minimum reqd. beam energy 12.5 GeV for J/ψ and 15 GeV for excited states: hardly enough energy in Fair I AA collisions.
Even in FAIR II, Cross-section will be very small.
J/ψ will be produced nearly at rest, so $\tau_f <$ medium formation time.
Excellent opportunity to study $\bar{c}c$ production at low energies.

Feeddown

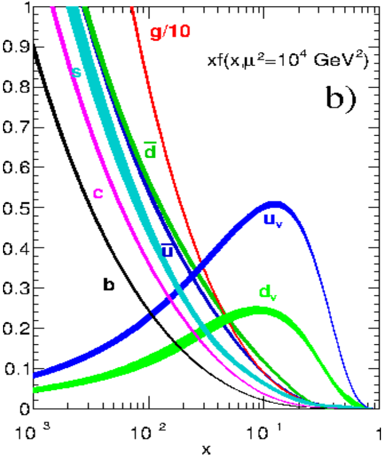


H.K. Wöhri, in QWG 2014

The fraction of J/ψ that comes from decay of excited states is likely to be suppressed already at lower temperatures.
Note this fraction is strongly p_T dependent.
For ALICE forward rapidity, $\sim$ 15% of J/ψ with $p_T < 2$ GeV come from feeddown while for $p_T \sim 8$ GeV this fraction is $\sim$ 30%.
Would be great to have the χ feeddown data at midrapidity also.

Nuclear distribution functions

Are the parton distribution functions in nucleus-nucleus collisions the same as those in $p - p$?



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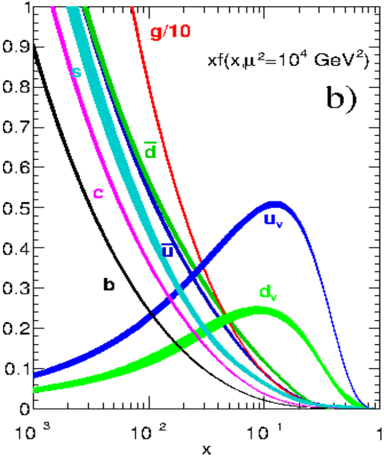
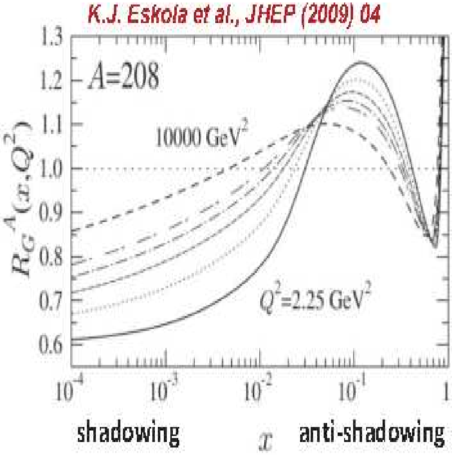
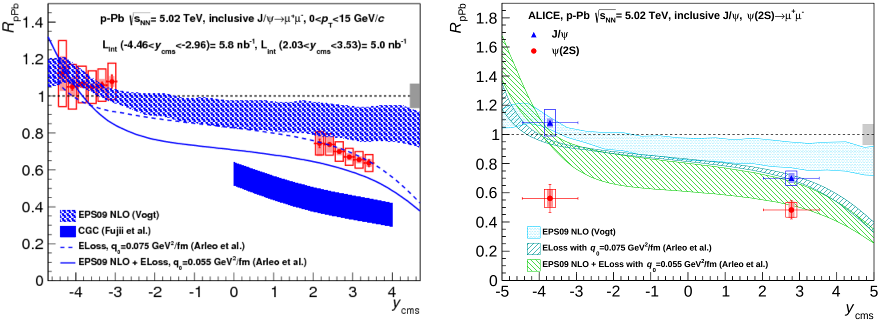



K.J. Eskola et al., JHEP (2009) 04

$p - N$ collisions

For the first (nuclear distribution function) and last (interaction with hadronic matter) questions: study $p - N$ collisions.



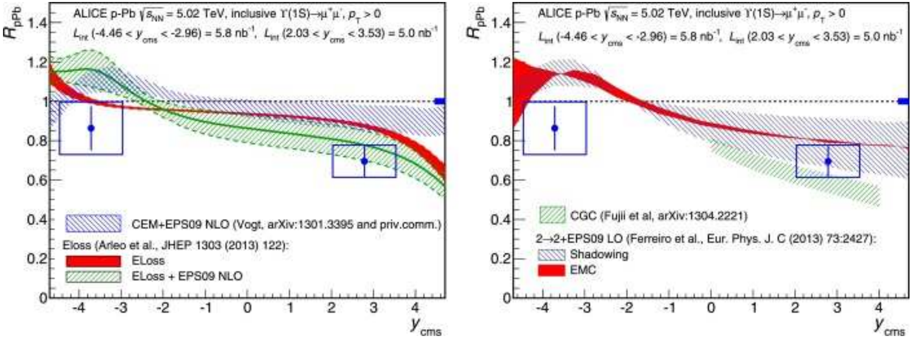
ALICE, JHEP 02 (2014) 073; D. Caffarri for ALICE, 1606.03970

Energy loss (of color octet pre-quarkonia) explain the data well, while some effect of antishadowing also seen.

Final state absorption

- To explain ψ' data, need to include final state absorption effect.
- For 5 TeV runs, $\sigma^{J/\psi} \approx 0.65$ mb, $\sigma^{\psi'} \approx 6$ mb reqd.
  Albacete et al., 1605.09479
- *For comparison, at SPS, at 400 A GeV p-Pb collisions, $\sigma^{J/\psi} \approx$ 4.3 mb and $\sigma^{\psi'} \approx$ 7.9 mb was found, while at 158 A GeV, $\sigma^{J/\psi} \approx$ 7.6 mb was required.*
- $\Rightarrow$ strong energy dependence. Expected to grow even larger at FAIR energies. A pA run will be absolutely essential.

Υ in $p - N$ collisions



ALICE, PL B 740 (2015) 105

$\Upsilon(2S)$ suppression similar to $\Upsilon(1S)$: final state suppression not important for Υ.

Lessons to carry

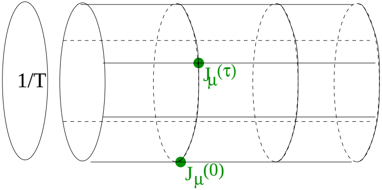
- Need to understand the production mechanism, as it affects the pre-resonance energy loss.
  The production mechanism in CBM is bound to be different from the high energy case.
- Feeddown fraction: complicated p_T dependence. At low p_T feeddown fraction could be less than assumed before.
  Feeddown fraction in CBM can be very different from high energy experiments.
- pN substantially different from $pp \times A$: need to take into account suppressions without medium formation.
- Data seems to prefer some amount of in-medium energy loss of the initial gluons, besides shadowing related effects.
- For charmonia, significant final state ("comover") effects also.
  Specially important for CBM.
- Bottomonia cleaner as far as final state effects are concerned.
  Unfortunately, not important for CBM.

In-medium behavior

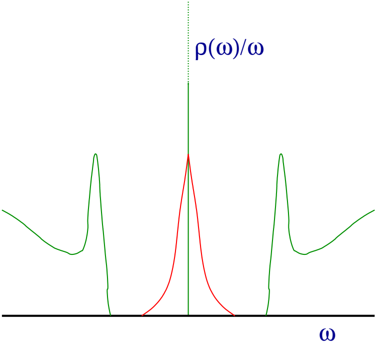
How to calculate interaction of quarkonia with medium?

QCD in non-perturbative regime: Lattice QCD

Calculate thermal (Matsubara) correlation function



Extract spectral function



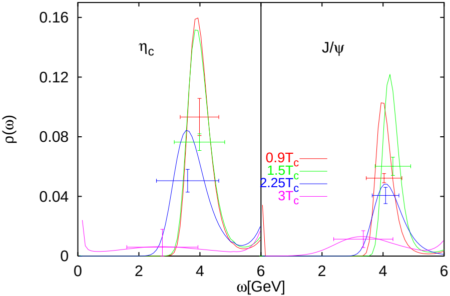
Extraction of spectral function complicated, not very stable even with Bayesian techniques.

Charmonia from lattice

- First studies: 1S charmonia survive till quite deep in plasma, while the 1P states dissolve early.

  Datta, Karsch, Petreczky, Wetzorke, 2004; Asakawa & Hatsuda, 2004; Matsufuru et al., 2005

- Gradual dissociation through thermal broadening.



But correlators are also consistent with other scenarios.

Umeda, 2007; Mocsy and Petreczky, 2007-2009.

Bottomonia from lattice

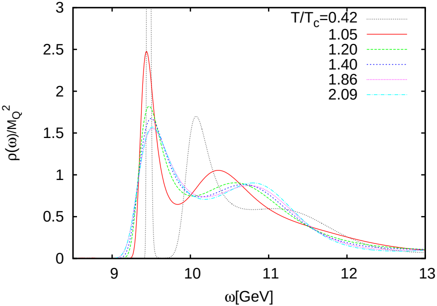
- Study of bottomonia difficult as large discretization error ($m_b a \sim 1$)
- Study using NRQCD: $\Upsilon(1S)$ and $\eta_b(1S)$ survive till $> 2T_c$
  However, large width: $\sim$ 400 MeV at 1.5 T_c

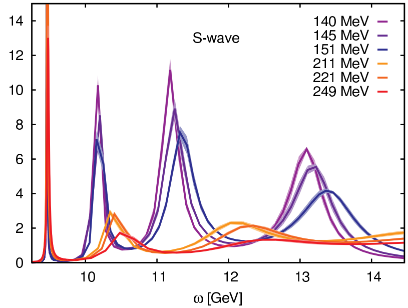
  G. Aarts, et al., JHEP 1111 (2011), 103; JHEP 1312 (2013) 064.
- χ_b drastically modified in the plasma.

  Aarts et al.
- Much smaller width of $\Upsilon(1S)$ found in a recent study.

  S. Kim, P. Petreczky and A. Rothkopf, arXiv:1409.3630.

Bottomonia from NRQCD





2-flavor QCD, $T_c \sim 219$ MeV

Aarts et al.

Kim et al.

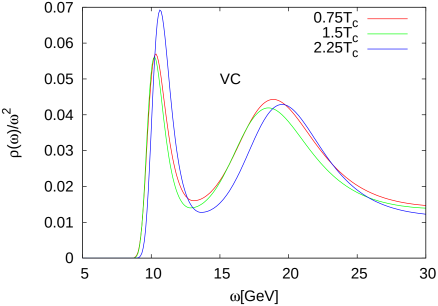
Rather large width

Much narrower width

Relativistic study at 1.5 T_c

- Gluonic plasma: can use sufficiently fine lattices, $a^{-1} \sim 10$ GeV, and nonperturbatively $\mathcal{O}(a)$ improved bottom action.
- For thermal decay of bottomonia, thermal quarks not expected to be important.

D. Kharzeev & H. Satz, Phys. Lett. B334 (1994) 155

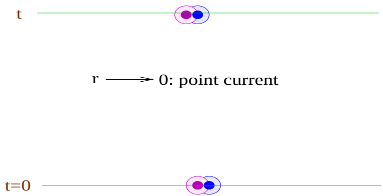


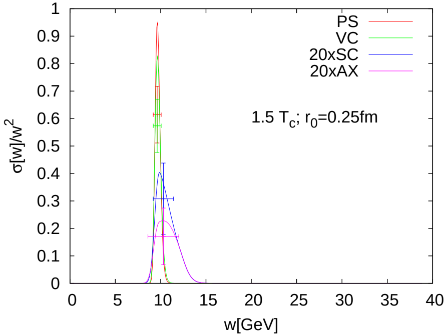
- No dramatic change on crossing T_c
- Indicative of survival of $\Upsilon(1S)$ upto quite high temperatures.
- Point correlator not very sensitive to width

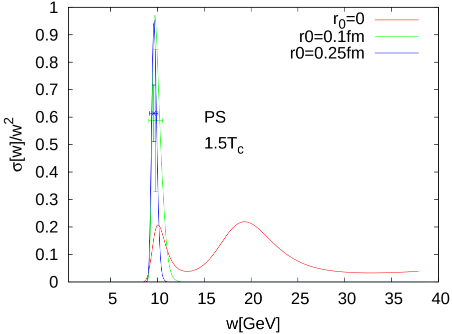
Smeared correlators

Use Gaussian smeared currents, to isolate the behavior of the lowest state

Note: this current does not directly connect to dilepton channel.





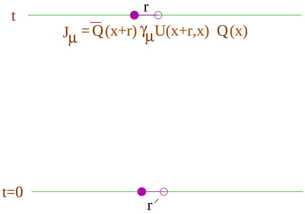


Potential

Can one write down a potential to describe in-medium quarkonia?

$$C(t) = \int d^3x \langle J_\mu(\vec{x},t) J_\mu(\vec{0},0)\rangle_T$$

$$i\partial_t C(t;r,r') =$$
$$(2M_Q + V(t;r,r'))\, C(t;r,r')$$
$$+\mathcal{O}(1/M_Q) \qquad \text{Defn.}$$



The potential has been calculated assuming a separation of scales

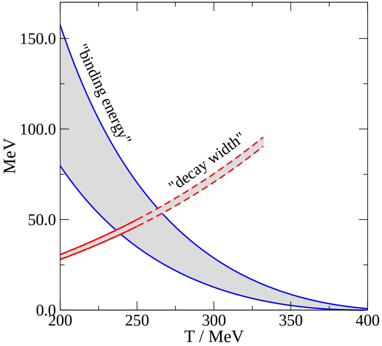
$$m_Q \gg T \gg g^2 M \gtrsim gT \gg g^4 M \gg \Lambda_{QCD}$$

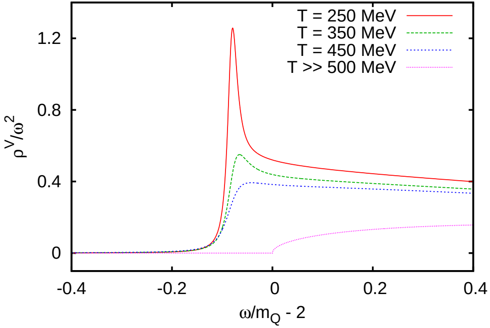
$$V(r) \;= -\frac{4}{3}\alpha_s \left(\frac{e^{-m_D r}}{r} + m_D\right) - i\frac{8}{3}\alpha_s T\, \Phi(m_D r)$$

M. Laine et al., JHEP 0703 (2007) 054; Brambilla et al., PRD 78 ('08) 014017.

Results from potential

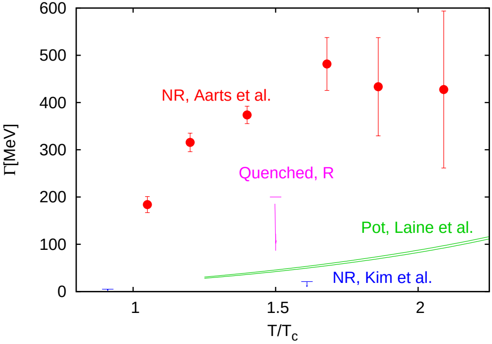
- Perturbative.
- $M_Q \gg T$
- Let us look for behavior of bottomonia.



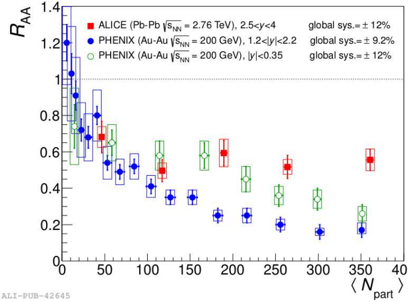


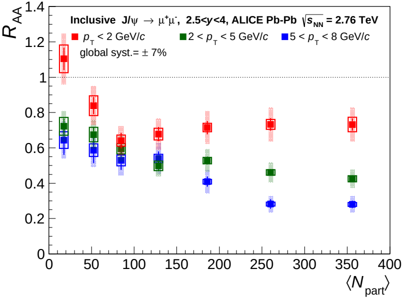
Burnier, Laine, Vepsalainen, JHEP ('11)

Width of $\Upsilon(1S)$



J/ψ in AA collisions





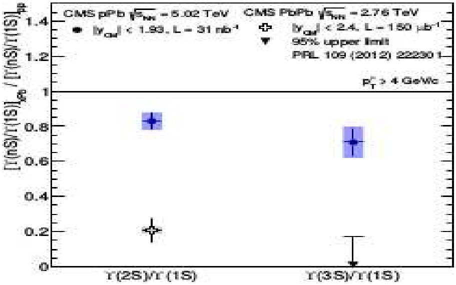
D. Caffarri for ALICE, 1606.03970

Besides the primordial J/ψ, need to admit in-medium generation.
Rate equation with gain and decay terms.

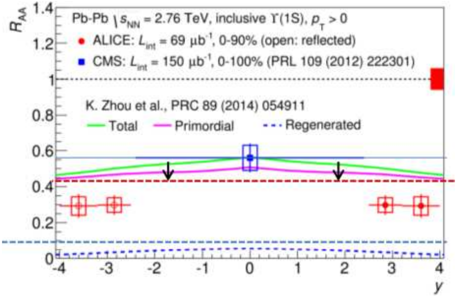
Zhao & Rapp, Nucl.Phys.A 859(2011)114; Zhao et al, Ph.Rev.C89(2014)054911.

Υ in LHC

Cleaner theoretically. Regeneration small. NRQCD works better.



N. Filipovic,J.Ph.conf.612(2015)012021



X. Lopez, Heavy flavor meet, SINP 2016

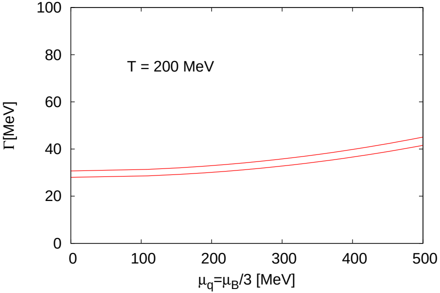
Regeneration also plays a role for $\Upsilon(1S)$?
CBM will be clean in this respect: charm density too little for regeneration to play a role even for J/ψ.

Potential at finite μ

At finite μ one needs to worry about the additional scale μ. For $\pi T \ll \frac{g\mu}{\pi} \ll M$, the dominant term in the static potential comes from Fermi surface effect: (Kapusta & Toimela (1987))

$$\mathrm{Re}\, V(r) \sim -\frac{\alpha(\mu)^2}{2\pi}\, e^{-2\pi T r}\, \frac{\sin 2\mu r}{\mu^3 r^4}$$

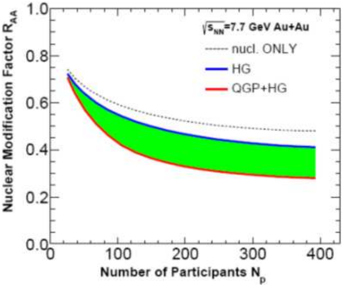
On the other hand, for $\pi T \gg \frac{g\mu}{\pi}$ the leading term is the Debye term, with $m_D \equiv m_D(\mu, T)$.
Can make an estimate of the width using this term.
Works better for $\Upsilon(1S)$.
(see also Chakraborty & Chattopadhyay, 1401.1110; Patra & Kakade, 1503.08149)



Some studies

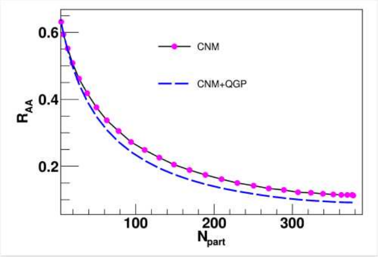
Chen, 1510.07902

- $\sigma_{\rm abs} = 4.3$ mb for J/ψ Underestimated?
- Gluodissociation in QGP (Peskin & Bhanot)
- Evolution through Boltzmann equation



Bhaduri et al., PRC 88(2013) 061902

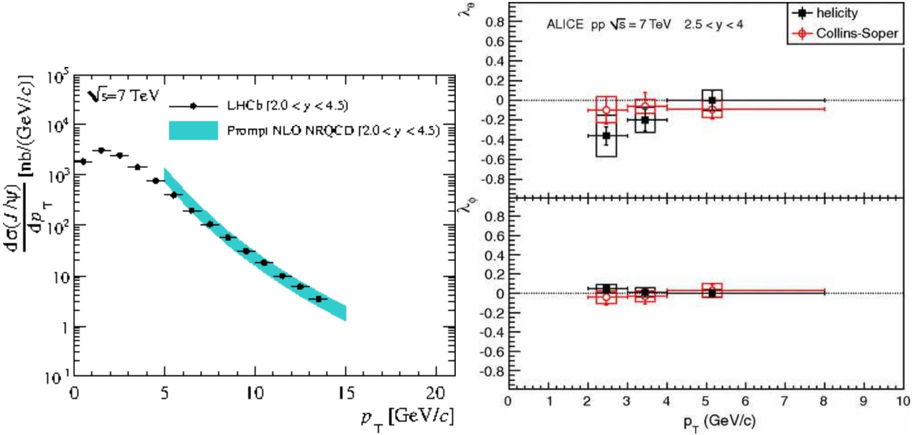
- Medium evolution: UrQMD
- Debye screening as threshold effect
- $\sigma_{\rm abs} = $ 12-15 mb for J/ψ



Summary

- Quarkonia has become a very important testing ground for our ideas of strongly interacting QGP.
- The RHIC and LHC data, taken together, offer many interesting puzzles.
- Explanation of the data requires understanding of cold nuclear matter effects, as well as properties of QGP using tools of lattice QCD and effective field theory.
- Charm production cross section will be orders of magnitude suppressed in CBM compared to the LHC.
- Study of quarkonia at CBM will provide us an excellent opportunity to study low energy $\bar{c}c$ production, and J/ψ absorption in nucleus.
- It will also provide us with an excellent tool to understand behavior of high baryon density plasma.

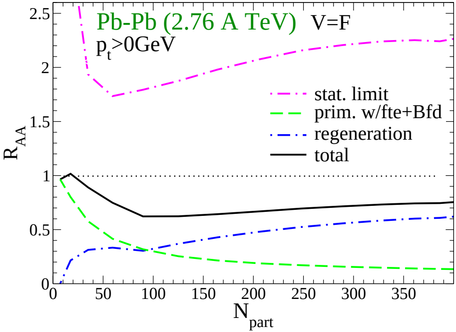
Extra: Quarkonia production

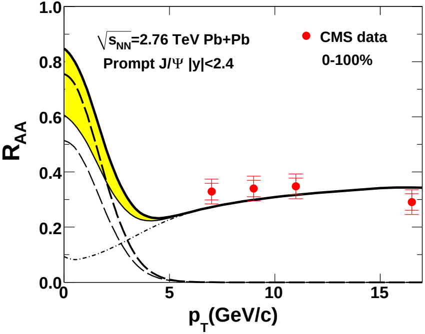


LHC, EPJC71 (2011) 1645; ALICE, PRL 108 (2012) 082001.

Extra: “Regeneration” at freeze-out

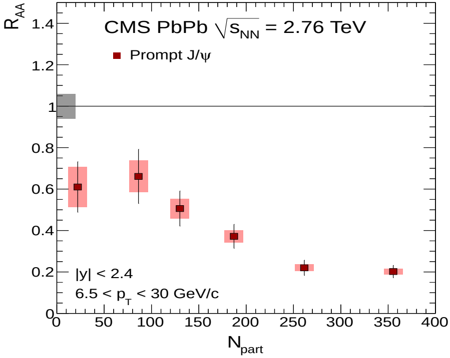
One way to understand the pattern is to take into account the possibility that because of large density of $c, \bar{c}$, at freezeout they may coalesce to form a J/ψ.
Will explain the centrality and rapidity dependence. However, the p_T dependence not steep enough for a thermal distribution.

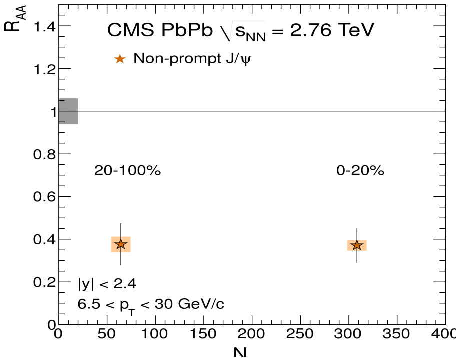




Zhao & Rapp, Nucl.Phys.A 859(2011)114; Zhao et al, Ph.Rev.C89(2014)054911.

Extra: Promt vs. Non-prompt J/ψ





CMS, JHEP 05 (2012) 063

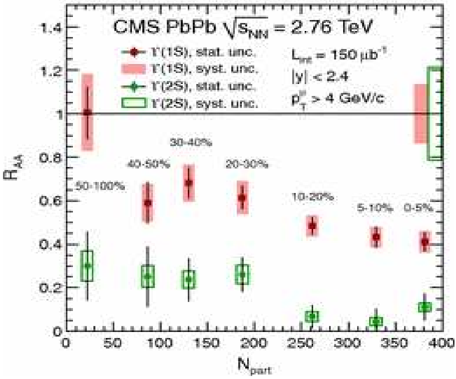
ALICE midrapidity ($|y| < 0.8$), 0 - 50% central: (JHEP 07 (2015) 051)

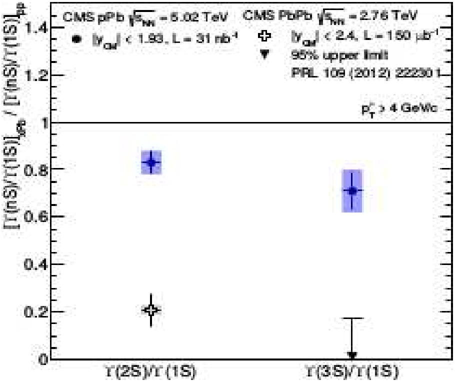
p_T (GeV)	f_B(%)	R_{AA} (inclusive)	R_{AA} (prompt)	R_{AA} (non-prompt)
1.5 - 4.5	10.7 ± 5.4	0.76 ± 0.12	0.76 ± 0.13	0.73 ± 0.39
4.5 - 10.0	17.0 ± 6.5	0.38 ± 0.09	0.38 ± 0.09	0.37 ± 0.17

Extra: Υ in LHC

Cleaner theoretically. Regeneration small. NRQCD-based estimates work better.

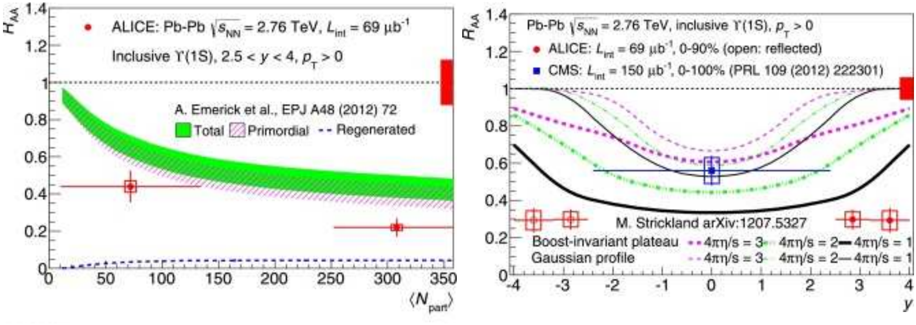
Strong suppression of excited states.





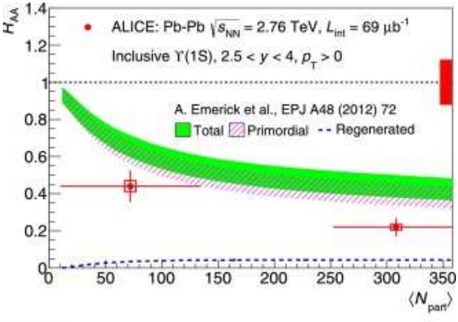
CMS, PRL 109 (2012) 222301. N. Filipovic for CMS, J.Phys.conf.612(2015)012021

Extra: Υ at forward rapidity

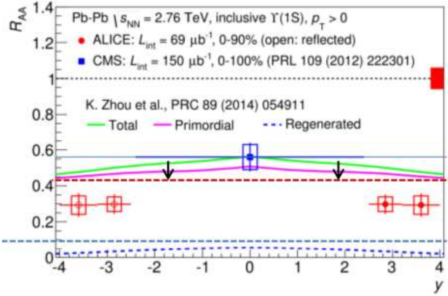


ALICE, Phys. Lett. B 738 (2014) 361.

Extra: Υ at forward rapidity



ALICE, Phys. Lett. B 738 (2014) 361.



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