The Quarkonium Analysis of the QGP: Fixed Target Aspects

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ECT* Workshop AFTER **February 2013**

Statistical QCD shows
$\exists$ color deconfinement,
$\exists$ hot quark-gluon plasma,
for $T > T_c$;

but it does not tell us
what thermometer can measure temperature
to identify a hot, deconfined medium.

Only measurable observables are observables.

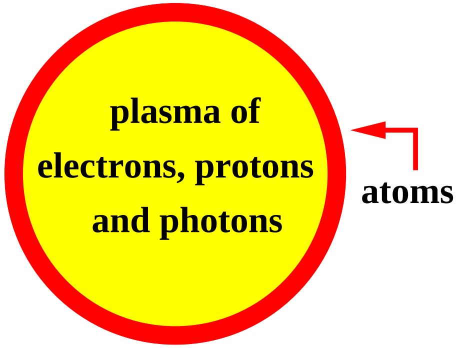
What can we use as QGP Thermometer?

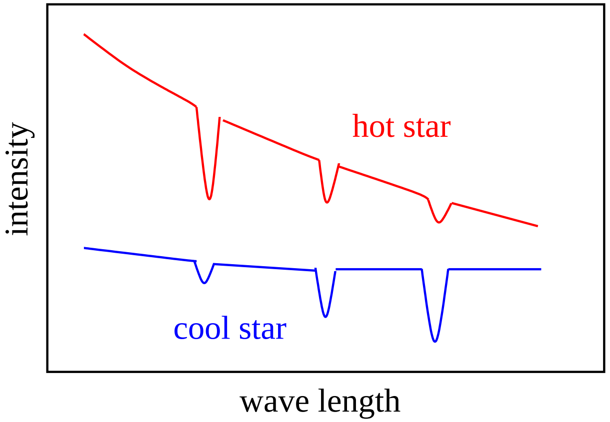
hadron abundances ⇒ hadronization stage of QGP

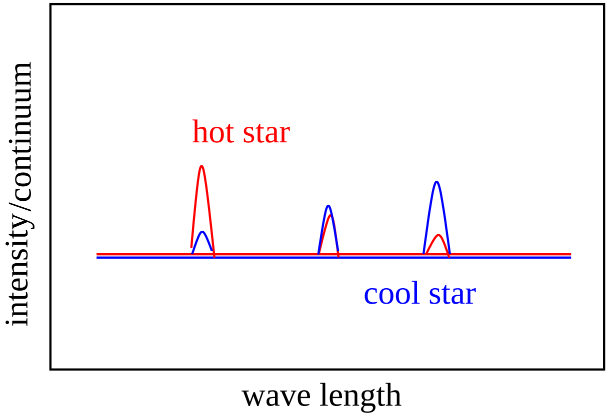
∃ probe of earlier hot QGP,
not accessible to direct measurements?

∃ a similar problem in astrophysics:
How does one measure temperatures of stellar interiors?

photons from plasma core are emitted,
absorbed by atoms in crust, lead to
absorption lines in stellar spectra







- **absorption lines indicate presence of atomic species**
- **absorption strength gives temperature of stellar interior**

Conjecture: Quarkonia are the spectral lines of the QGP

Matsui & HS, 1986

∃ no crust of QGP, but ∃ early hard production of quarkonia

**they're there when QGP appears, and its effect
on different quarkonium states tells how hot the QGP is.**

Contents

1. Quarkonia are very unusual hadrons
2. Quarkonia melt in a hot QGP
3. Quarkonium production is suppressed in nuclear collisions
4. Quarkonia can be created at QGP hadronization
5. Quarkonium behavior must be determined by correct reference

1. Quarkonia are very unusual hadrons

heavy quark ($Q\bar{Q}$) bound states stable under strong decay

- heavy: $m_c \simeq 1.2 - 1.4$ GeV, $m_b \simeq 4.6 - 4.9$ GeV
- stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

What is "usual"?

- light quark ($q\bar{q}$) constituents
- hadronic size $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm, independent of mass
- loosely bound, $M_\rho - 2M_\pi \gg 0,\ \ M_\phi - 2M_K \simeq 0$
- relative production abundances $\sim$ energy independent, statistical: at large $\sqrt{s}$, rate $R_{i/j} \sim$ phase space at T_c
- $(dN_{\rm ch}/dy) \sim \ln s$

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, $\alpha = \pi/12$)

excellent account of full quarkonium spectroscopy:

spin-averaged masses , binding energies, radii.

masses to better than 1 %...

NB:

recent work on field theoretical quarkonium studies,

NRQCD Brambilla & Vairo 1999, Brambilla et al. 2000

$\Rightarrow$ **quarkonia are unusual**

– **very small, mass-dependent size:**

$$r_{J/\psi} \simeq 0.25 \text{ fm}, \; r_{\Upsilon} \simeq 0.14 \text{ fm} \quad \ll \Lambda_{\text{QCD}}^{-1} \simeq 1 \text{ fm}$$

– **very tightly bound:**

$$\left.\begin{array}{l} 2M_D - M_{J/\psi} \simeq 0.64 \text{ GeV} \\ 2M_B - M_{\Upsilon} \quad \simeq 1.10 \text{ GeV} \end{array}\right. \gg \Lambda_{\text{QCD}} \simeq 0.2 \text{ GeV}$$

production of heavy vs. light flavors in elementary collisions:

- $(dN_{c\bar{c}}/dy) \sim s^a$
- $(dN_{\rm ch}/dy) \sim \ln s$
- $N_{c\bar{c}}/N_{\rm ch}$ grows with collision energy compare $[N_{s\bar{s}}/N_{\rm ch}]$

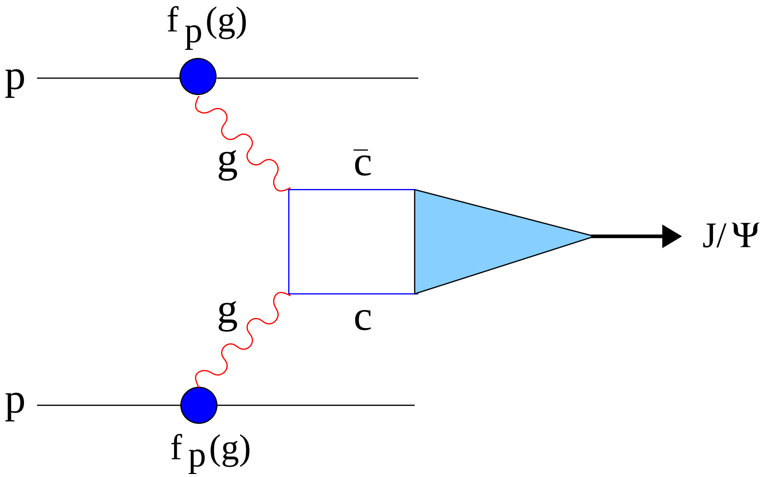
$\Rightarrow$ heavy flavor production is dynamical and not statistical

- $(dN_{J/\psi}/dy)/(dN_{c\bar{c}}/dy) \simeq 0.02$, compare $[N_{\rho}/N_{\rm ch}]$
  factor 10 bigger than ratio of statistical weights at T_c
  much more hidden charm than statistically predicted
- $(dN_{\psi'}/dy)/dN_{J/\psi}/dy) \simeq 0.2$, compare $[N_{\rho}/N_{\omega}]$
  factor five bigger than ratio of statistical weights at T_c
  ratios of states $\sim$ wave functions, not Boltzmann factors

$\Rightarrow$ quarkonium binding is dynamical and not statistical

primary production via partonic interaction dynamics

Einhorn & Ellis 1975, Baier & Rückl 1983, Lansberg 2006

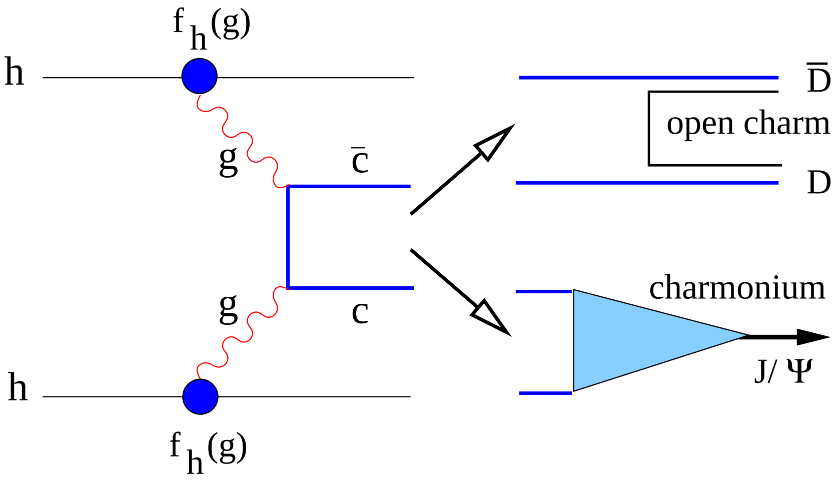


given parton distribution functions from DIS,
$c\bar{c}$ production is perturbatively calculable (cum grano salis)

J/ψ binding is not, but it is independent of collision energy:

$$R[(J/\psi)/c\bar{c}] \sim |\phi_{J/\psi}(0)|^2 \neq f(s)$$

same for excited states; overall effect:



hidden to open partititioning independent of collision energy;
why? $M(c\bar{c})$ increases very slowly

in elementary collisions (no medium)

~ 90% open charm, ~ 10 % charmonium.
charmonium sector ~ 28% 1S, 65% 1P, 7% 2S

Quarkonium production in elementary collisions $\sim$ no medium

What happens to quarkonia in hot strongly interacting media?

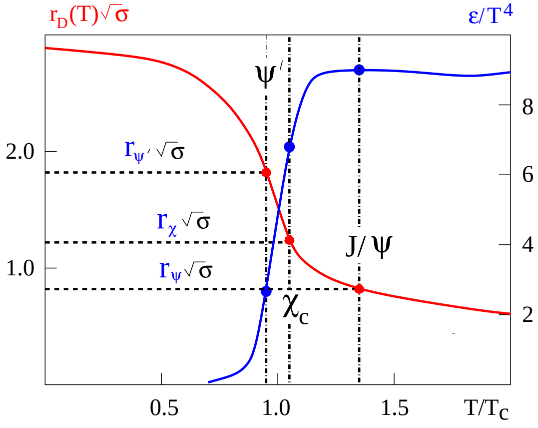
2. Quarkonia melt in a hot QGP

Matsui & HS 1986, Karsch et al. 1988

- QGP consists of deconfined color charges, hence
  $\exists$ color screening for $Q\bar{Q}$ state
- screening radius $r_D(T)$ decreases with temperature T
- if $r_D(T)$ falls below binding radius r_i of $Q\bar{Q}$ state i,
  Q and $\bar{Q}$ cannot bind, quarkonium i cannot exist
- quarkonium dissociation points T_i, from $r_D(T_i) = r_i$,
  specify temperature of QGP

Color screening ⇒ binding weaker and of shorter range

when force range/screening radius become less than binding radius, Q and $\bar{Q}$ cannot “see” each other



⇒ quarkonium dissociation points

determine temperature ⇒ energy density of medium

How to calculate quarkonium dissociation temperatures?

- determine heavy quark potential $V(r,T)$ in finite temperature QCD, solve Schrödinger equation
- calculate in-medium quarkonium spectrum $\sigma(\omega,T)$ directly in finite temperature lattice QCD

- Heavy Quark Studies in Finite Temperature QCD

Hamiltonian $\mathcal{H}_Q$ for QGP with color singlet $Q\bar{Q}$ pair:

$$F_Q(r,T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_Q/T\}$$

Hamiltonian $\mathcal{H}_0$ for QGP without $Q\bar{Q}$ pair:

$$F_0(T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_0/T\}$$

study free energy difference $F(r,T) = F_Q(r,T) - F_0(T)$

internal energy difference $U(r,T)$ & entropy difference $S(r,T)$

$$U(r,T) = -T^2 \left(\frac{\partial [F(r,t)/T]}{\partial T} \right) = F(r,T) + TS(r,T)$$

What is the potential? $V = U$ or $V = F$ or mixture?

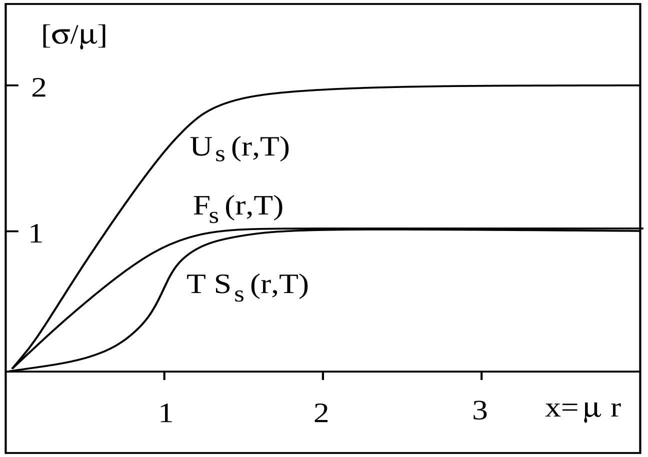
For illustration, parametrize lattice results as

$$F_s(r,T) = \sigma r \left[\frac{1 - e^{-\mu(T)r}}{\mu(T)r}\right] = \frac{\sigma}{\mu(T)}\left[1 - e^{-\mu(T)r}\right]$$

this gives

$$T\,S_s(r,T) = \frac{\sigma}{\mu}\left[1 - (1+\mu r)e^{-\mu r}\right]$$

$$U_s(r,T) = \frac{\sigma}{\mu}\left[2 - (2+\mu r)e^{-\mu r}\right]$$



need one σ/μ to separate Q and $\bar{Q}$, and another σ/μ to form polarization clouds (entropy change)

Who pays for what?

$V(r,T) = U(r,T)$ — the heavy quark pair pays all

$V(r,T) = F(r,T)$ — the medium pays the entropy change

$V(r,T) = xF(r,T) + (1-x)U(r,T)$

— medium and pair split the entropy cost

the more the pair pays, the tighter is its binding....with obvious consequences on dissociation temperatures

indicative results

for T_{diss}/T_c

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

Digal et al. 2001; Shuryak & Zahed 2004; Wong 2004/5; Alberico et al. 2005;
Digal et al. 2005; Mocsy & Petreczky 2005/6

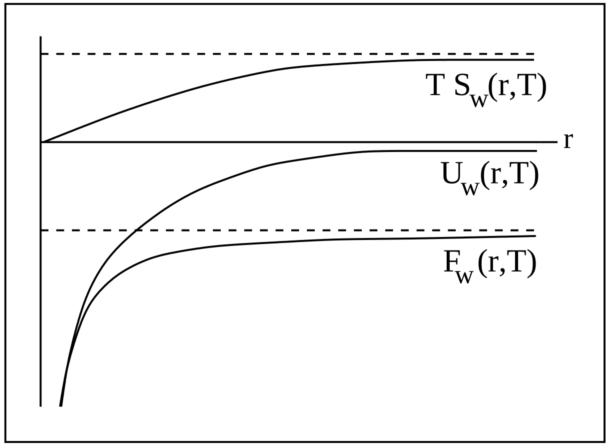
Is there a theoretical way to decide between F and U?

In weak coupling regime (Debye-Hückel, QED) yes:

$$F(r,T) = V(r,T) = -\alpha\left[\mu(T) - \frac{1}{r}e^{-\mu(T)r}\right]$$

Laine et al. 2007, Beraudo et al. 2008, Brambilla et al. 2008, Escobedo & Soto 2008, Burnier et al. 2009

but applies to very different dynamics:



short distance limit

$F_w(r,T) = U_w(r,T) = -\frac{\alpha}{r}$

$TS_w(r,T) \to 0$

large distance limit

$-F_w(r,T) = TS_w(r,T) \to (\alpha\mu/2)$

$U_w(r,T) \to 0$

melting process: work to separate $Q\bar{Q}$ converted into entropy

- Lattice Studies of Quarkonium Spectrum

Calculate correlation function $G_i(\tau,T)$ for mesonic channel i determined by quarkonium spectrum $\sigma_i(\omega,T)$

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

relates imaginary time τ and $c\bar{c}$ energy ω through kernel

$$K(\omega,\tau,T) = \frac{\cosh[\omega(\tau - (1/2T))]}{\sinh(\omega/2T)}$$

invert $G_i(\tau,T)$ to get quarkonium spectra $\sigma_i(\omega,T)$

Basic Problem

correlator given at discrete number $N_\tau/2$ of lattice points, $N_\tau \sim 50 - 100$; want spectra $\sigma_i(\omega,T)$ at ~ 1000 points in ω

- brute force solution: calculate correlators for $N_\tau = 2000$ then inversion is well-defined – project for FAR distant future
- in the meantime: invert $G(\tau, T)$ by MEM to get $\sigma(\omega, T)$

Maximum Entropy Method (MEM)

here: Asakawa and Hatsuda 2004

what is the most likely solution for given data, given errors and some basic information?

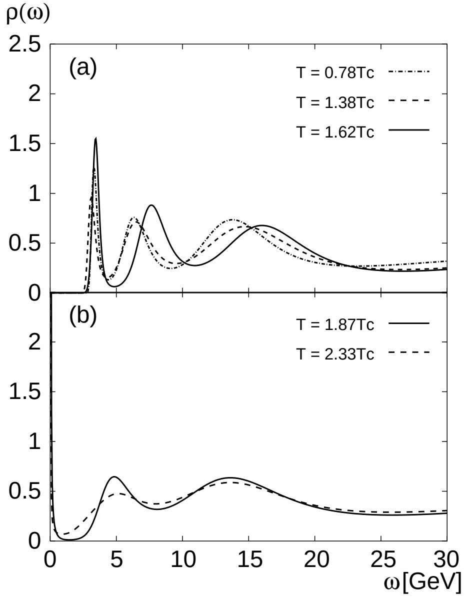
charmonia quenched:

Umeda et al. 2001
Asakawa & Hatsuda 2004
Datta et al. 2004
Iida et al. 2005
Jakovac et al. 2005

charmonia unquenched:

Aarts et al. 2005, 2007

first results $\Longrightarrow$



- **MEM requires input reference (“default”) function for σ; form of and dependence on default function?**

Preliminary work:

- **present information insufficient for resonance width**
- **present information sufficient for ground state position below T_c, dubious above T_c**
- **better statistics, larger N_τ should resolve MEM results for $T > T_c$**
- **very much larger N_τ could (eventually) resolve resonance width**

Tentative summary so far:

- **J/ψ survives up to $T \simeq 1.5\ T_c$**
- **χ and ψ' dissociated at or slightly above T_c**

$\exists$ observable consequences for nuclear collision experiments?

3. Quarkonium production is suppressed in nuclear collisions

...but for a variety of reasons

- nuclear modifications of parton distribution functions
- parton energy loss in cold nuclear matter
- pre-resonance dissociation in cold nuclear matter
- dissociation by color screening ("melting") in hot QGP

How to sort things out? Procedure up to now:

- determine initial & final state cold nuclear matter effects from pA, model AA, check if $\exists$ further *anomalous suppression*

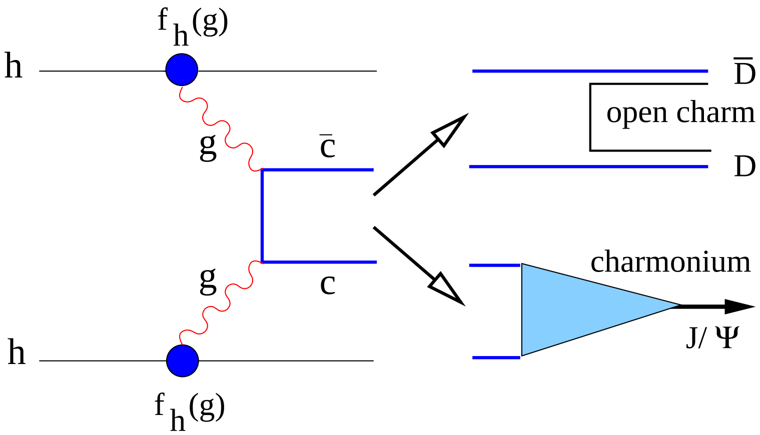
$\Rightarrow$ interesting results, 25 years without definite conclusion

∴ chose a correct reference to eliminate initial state effects

recall heavy flavor production:

proton-proton (no medium)

- 90% open charm,
  10 % charmonium
- measured J/ψ: 60% 1S,
  30% χ_c decay, 10% ψ' decay.



so the decisive questions are

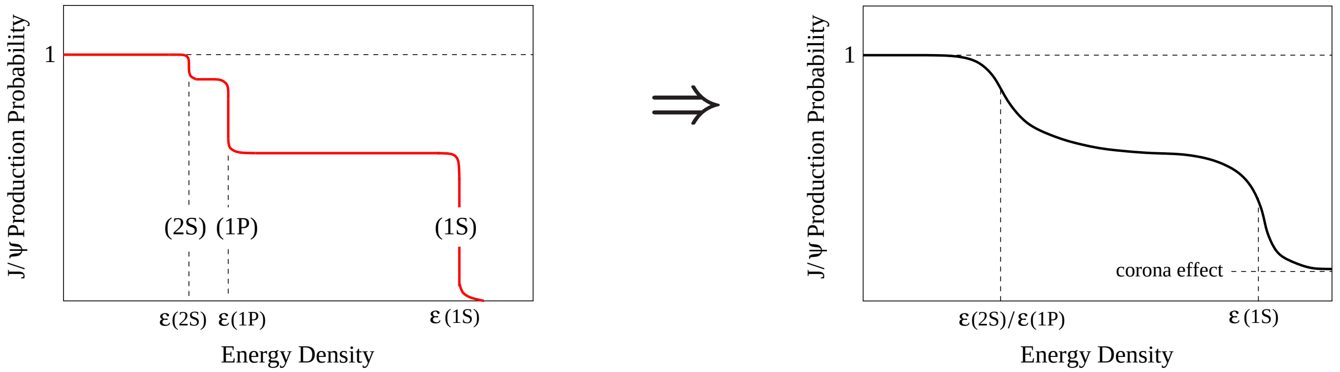
- does presence of a medium change the relative fractions of hidden vs. open heavy flavor production?
- does presence of a medium change the relative production rates of the different charmonium or bottomonium states?

How can the hot medium change the hidden/open fractions?

color screening in hot QGP ⇒ sequential J/ψ suppression

Karsch & HS 1991; Gupta & HS 1992; Karsch, Kharzeev & HS 2006

- narrow excited states decay outside medium ⇒ medium affects excited states per se
- J/ψ survival rate shows sequential reduction: first due to ψ' and χ_c melting, then later direct J/ψ dissociation
- experimental smearing of steps; corona effect



When quarkonium suppression thresholds are calculable, and

When quarkonium suppression thresholds are measurable,

Then they provide a quantitative test of statistical QCD.

Does a sufficiently hot QGP $\Rightarrow$
no charmonium production at the LHC?

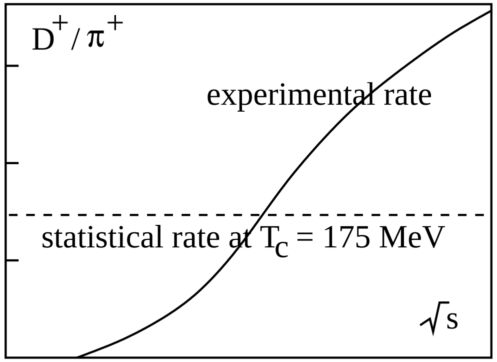
– corona effect

– significant B production $\rightarrow$ charmonium production via feed-down from B decay; check through pp studies. And:

4. Quarkonia can be created at QGP hadronization

Braun-Munzinger & Stachel 2001, Thews et al. 2001, Grandchamp & Rapp 2002
Andronic et al. 2003, Zhuang et al. 2006

- **$c\bar{c}$ production is a dynamical** *hard process* **:** **at high energy, produced medium contains more than the** *statistical* **number of charm quarks**



- **assume**
  - **charm quark abundance constant in evolution to T_c**
  - **charm quarks form part of equilibrium QGP at T_c**
  - **equilibrium QGP at T_c hadronizes statistically**
  - **charmonium production via statistical $c\bar{c}$ fusion**

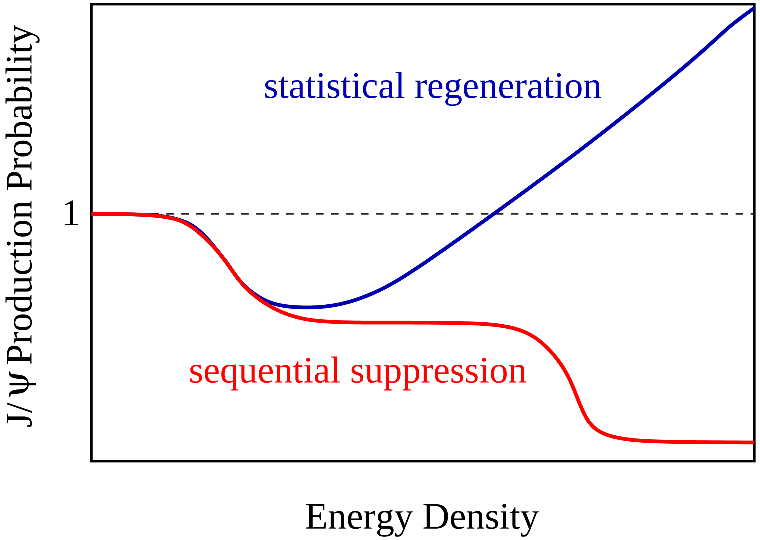
- **"secondary" charmonium production by fusion of c and $\bar{c}$ produced in different primary collisions**

- **insignificant at "low" energy, since very few charm quarks; could be dominant production mechanism at high energy**

Secondary statistical J/ψ production implies that in sufficiently high energy nuclear collisions

- J/ψ production is strongly enhanced re scaled pp rate
- ratio of hidden/open charm strongly enhanced re pp ratio

two readily distinguishable predictions for anomalous J/ψ production



dynamical vs. statistical momentum spectra Mangano & Thews 2003

NB: assumption of statistical quarkonium binding...

If ∃ statistical regeneration of charmonium at the LHC,

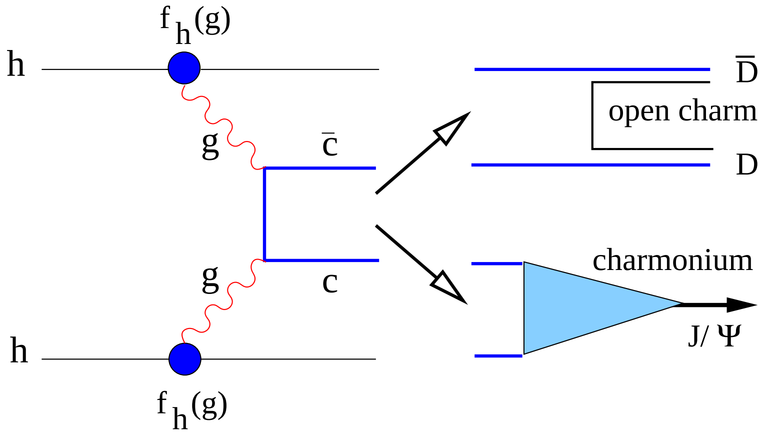
– use sequential suppression in bottomonium production as tool to compare heavy ion data to QCD calculations

– do a high statistics charmonium study at low enough energy to avoid regeneration (reduce charm production)

5. Correct reference for quarkonium behavior

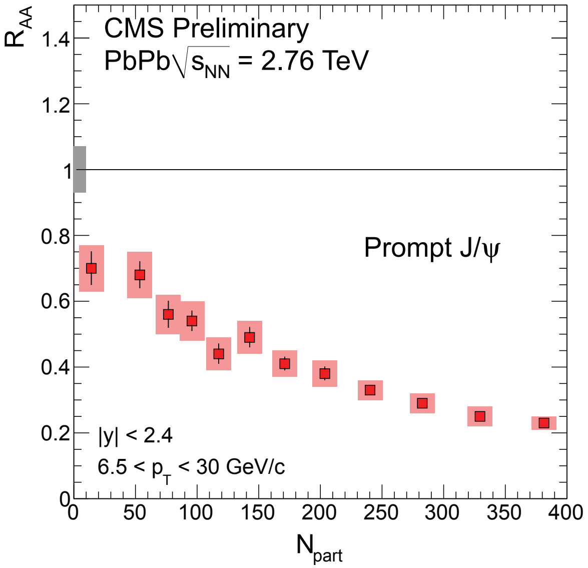
recall heavy flavor production:

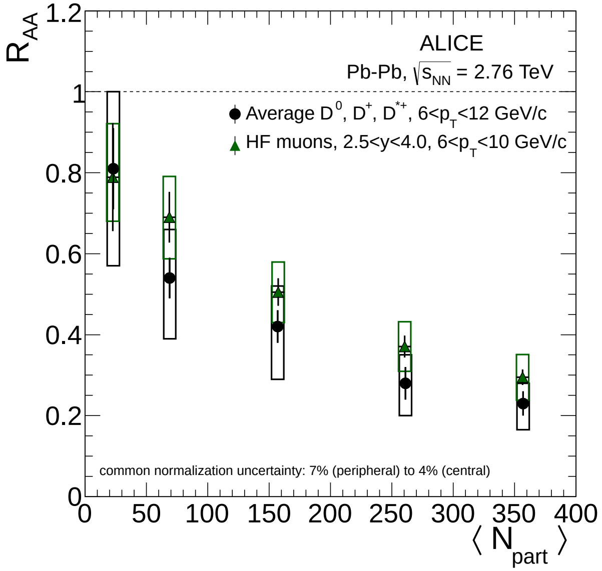
in elementary collisions
(no medium)
90% open charm,
10 % charmonium.



⋆ Does presence of a medium change the relative fraction of $c\bar{c}$ or $b\bar{b}$ production going into hidden vs. open heavy flavor?

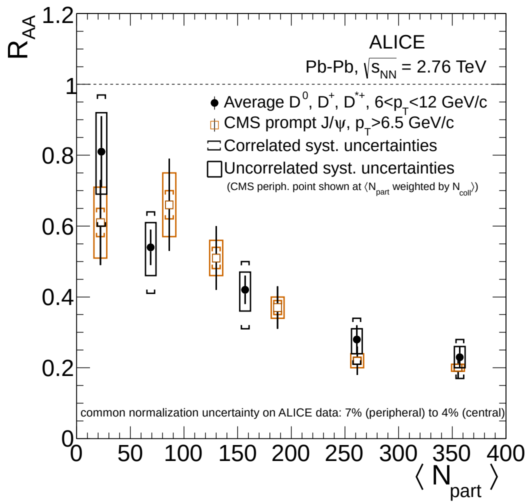
- Quarkonium suppression/enhancement means reduction/increase of hidden to open heavy flavor production; all initial state effects are eliminated, only medium effects on quarkonia (in all evolution stages) remain.
- Determining suppression re pp production rate (R_{AA}) *can* be very misleading:





- **Quarkonium suppression/enhancement means reduction/increase of hidden to open heavy flavor production; all initial state effects are eliminated, only medium effects on quarkonia (in all evolution stages) remain.**

- **Determining suppression re *pp* production rate ($\boldsymbol{R_{AA}}$) *can* be very misleading:**



Z. Conesa del Valle, QM2012

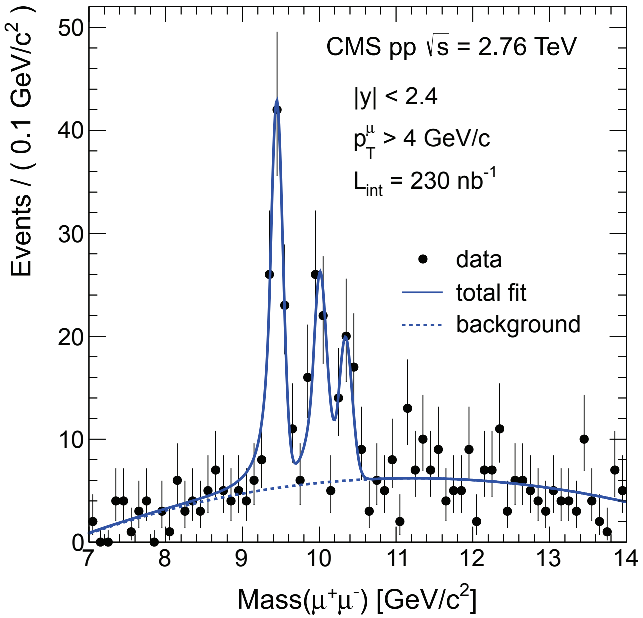
J/ψ reduced with centrality same as $c\bar{c}$; ratio hidden/open same as for no medium; correct J/ψ survival probability is unity, $\exists$ neither suppression nor enhancement.

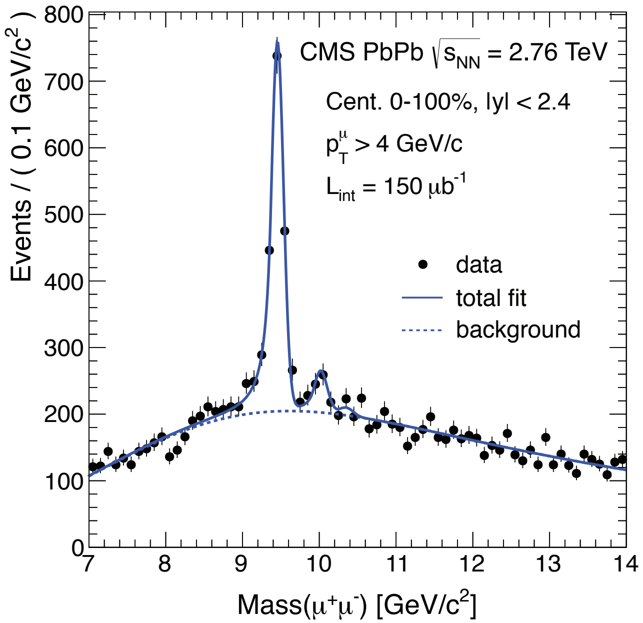
ALI−DER−38759

This was at high P_T; dominant contributions are at low P_T

- If total no. of $c\bar{c}$ pairs in AA is essentially that from pp scaled by the number of collisions, then any suppression observed for large P_T must be compensated by enhanced $c\bar{c}$ production at low P_T.
- RHIC finds a smaller $c\bar{c}$ suppression at large P_T than LHC, so LHC will have a larger low P_T enhancement of $c\bar{c}$ production than RHIC.
- If we determine suppression/enhancement re open charm, all this does not matter.
- But for R_{AA}, this alone will lead to an increased value of J/ψ production in central AA collisions for LHC, compared to RHIC.

- ⋆ **alternative to hidden/open: sequential suppression means reduction of (nS) states relative to $(1S)$ state in QGP.**





Evidence for sequential suppression? – see CMS paper

If initial state modifications do not vary significantly between $1S$ and nS mass, the $\boldsymbol{R_{AA}}$ ratios measure directly the relevant in-medium exited/ground state change:

$$\frac{\boldsymbol{R_{AA}(nS)}}{\boldsymbol{R_{AA}(1S)}} = \frac{\boldsymbol{N_{AA}(nS)}}{\boldsymbol{N_{AA}(1S)}} \Big/ \frac{\boldsymbol{N_{pp}(nS)}}{\boldsymbol{N_{pp}(1S)}}.$$

If this ratio is unity, no suppression; otherwise, its value gives the suppression amount and threshold.

⋆ **Hidden/open eliminates initial state effects. What about final state cold nuclear matter effects on evolving quarkonia?**

To resolve, measure quarkonium states re open flavor in $\boldsymbol{pA}$ and $\boldsymbol{pp}$.

Essential Requirements

Charmonia:

- hidden charm: J/ψ, χ_c, ψ' in pp, pA and AA
- open charm: D in pp, pA and AA
- all data at the same energy and in the same kinematic region
- energy ideally below regeneration level

Bottomonia:

- hidden beauty: Υ(1S), (2S), (3S); χ_b(1P), (2P) in pp, pA and AA
- open beauty: B in pp, pA and AA
- all data at the same energy and in the same kinematic region

Conclusions

Only measurements of hidden/open heavy flavor production,

measurements of excited/ground state quarkonium production

can provide conceptual [model-independent] answers to

conceptual [model-independent] questions.

Quantitative details require specific theory/model input.