Quarkonium in the statistical hadronization model
or better
Quarkonium and the phase boundary of QCD

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• Chemical freeze-out of light quark (u,d,s) hadrons
• ...and the connection to the QCD phase diagram
• Charmonium
• Bottomonium
• Outlook to full energy LHC and FCC

arXiv:1210.7724, 1409.5778 (and refs. therein)
Chemical freeze-out: hadron yields (central collisions)

lots of particles, mostly newly created \( (m = E/c^2) \)

\[ \frac{dN}{dy} \bigg|_{y=0} \]

\( N_{\text{part}} = 350 \)

- a great variety of species:
  \( \pi^\pm (u\bar{d}, \bar{u}d) \), \( m = 140 \) MeV
  \( K^\pm (u\bar{s}, \bar{u}s) \), \( m = 494 \) MeV
  \( p \ (uud) \), \( m = 938 \) MeV
  \( \Lambda \ (uds) \), \( m = 1116 \) MeV
  also: \( \Xi (dss) \), \( \Omega (sss) \)...

- mass hierarchy in production
  (at low en.: \( u, d \) quarks remnants from the incoming nuclei)

- chemistry explained by thermal model
  with 3 parameters: \( T, \mu_B, V \)
The statistical (thermal) model

grand canonical partition function for specie \(i\) \((\hbar = c = 1)\):

\[
\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln[1 \pm \exp(- (E_i - \mu_i)/T)]
\]

\(g_i = (2J_i + 1)\) spin degeneracy factor; \(T\) temperature;
\(E_i = \sqrt{p^2 + m_i^2}\) total energy; \((+\) for fermions \((-\) for bosons
\(\mu_i = \mu_B B_i + \mu_I I_3 i + \mu_S S_i + \mu_C C_i\) chemical potentials

\(\mu\) ensure conservation (on average) of quantum numbers, fixed by “initial conditions”

i) isospin: \(V_{cons} \sum_i n_i I_{3i} = I_3^{tot}\), with \(V_{cons} = N_B^{tot} / \sum_i n_i B_i\)
\(I_3^{tot}, N_B^{tot}\) isospin and baryon number of the system \((= 0\) at high energies)

ii) strangeness: \(\sum_i n_i S_i = 0\)

iii) charm: \(\sum_i n_i C_i = 0\)
Thermal fits of hadron abundances

\[ n_i = \frac{N_i}{V} = - \frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T]} \pm 1 \]

quantum no. conservation:
\[ \mu_i = \mu_B B_i + \mu_I I_3 i + \mu_S S_i + \mu_C C_i \]

Latest PDG hadron mass spectrum (up to 3 GeV, 485 species)

Minimize: \[ \chi^2 = \sum_i \frac{(N_i^{\text{exp}} - N_i^{\text{therm}})^2}{\sigma_i^2} \]

\( N_i \): hadron yield \( \Rightarrow (T, \mu_B, V) \)

Hadron abundances consistent with a thermally equilibrated system
Energy dependence of \( T, \mu_B \) (central collisions)

Thermal fits exhibit a limiting temperature:

\[
T = T_{\text{lim}} \frac{1}{1 + \exp(2.60 - \ln(\sqrt{s_{NN}(\text{GeV})})/0.45)},
\]

where

\[
T_{\text{lim}} = 159 \pm 2 \text{ MeV}
\]

and

\[
\mu_B[^{\text{MeV}}] = \frac{1307.5}{1 + 0.288 \sqrt{s_{NN}(\text{GeV})}}
\]

PLB 673 (2009) 142 ...with updates
Volume in central collisions

\[ V_{\text{chem}}(\Delta y = 1) = \frac{dN_{\text{ch}}/dy|_{y=0}}{n_{\text{therm}}} \]

\[ V_{\text{kin}}(k_T = 0.22 \text{ GeV/c}) \approx T(k_{\text{kin}}) \]

\[ V_{\text{kin}} = V_{\text{HBT}} = \left(2\pi\right)^{3/2} R_{\text{side}}^2 R_{\text{long}} \]

HBT data: ALICE, PLB 696, 328 (2011)

5.1 TeV: \( V = 6400 \text{ fm}^3 \)

40 TeV: \( V = 12000 \text{ fm}^3 \) (2.2x \( V_{2.76} \))
Connection to the phase diagram of QCD

(as $T \to T_{lim}$) is chemical freeze-out a determination of the phase boundary?

Lattice QCD, $\mu_B = 0$:
crossover $T=145-165$ MeV

BW, JHEP 1009 (2010) 073
HotQCD arXiv:1407.6387

...for entire $\mu_B$ range?

PBM, Stachel, Wetterich, PLB 596 (2004) 61
McLerran, Pisarski, NPA 796 (2007) 83
AA et al., NPA 837 (2010) 65
Floerchinger, Wetterich, NPA 890 (2012) 11
We turn now to quarkonium

\[ R_{\text{AA}} \]

\[ N_{\text{part}} \]

\[ Y(1S) \]

\[ Y(1S+2S+3S), \sqrt{s_{\text{NN}}}=0.2 \text{ TeV} \]

\[ \text{CMS (|y|<2.4, ±14% syst.), } \sqrt{s_{\text{NN}}}=2.76 \text{ TeV} \]

\[ \text{STAR (|y|<1.0, ±19% syst.), } \sqrt{s_{\text{NN}}}=0.2 \text{ TeV} \]

\[ \text{PHENIX (|y|<0.5, ±40% syst.)} \]

\[ \text{ALICE (|y|<0.8, ±13% syst.), } \sqrt{s_{\text{NN}}}=2.76 \text{ TeV} \]

\[ \text{ALICE (2.5<y<4.0, ±15% syst.), } \sqrt{s_{\text{NN}}}=2.76 \text{ TeV} \]

\[ \text{STAR (|y|<1.0, ±13% syst.), } \sqrt{s_{\text{NN}}}=0.2 \text{ TeV} \]

\[ \text{PHENIX (|y|<0.35, ±12% syst.), } \sqrt{s_{\text{NN}}}=0.2 \text{ TeV} \]

\[ \text{PHENIX (1.2<y<2.2, ±9% syst.), } \sqrt{s_{\text{NN}}}=0.2 \text{ TeV} \]

\[ 13\% \text{ syst.}, 15\% \text{ syst.}, 12\% \text{ syst.}, 9\% \text{ syst.} \]

\[ \pm \]

arXiv:1409.5778
Statistical hadronization of heavy quarks: assumptions


- all charm quarks are produced in primary hard collisions \( t_{cc} \approx 1/2m_c \approx 0.1 \text{ fm}/c \)
- survive and thermalize in QGP (thermal, but not chemical equilibrium)
- charmed hadrons are formed at chemical freeze-out together with all hadrons
- statistical laws, quantum no. conservation; stat. hadronization \( \neq \) coalescence
- is freeze-out at(/the?) phase boundary?
  ...we believe yes ...based on data in the light-quark sector (support from LQCD)
- no \( J/\psi \) survival in QGP (full screening)
  
  can \( J/\psi \) survive above \( T_c \)? ...yet to be settled (LQCD)

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if all this is supported by data, J/ψ loses status as “thermometer” of QGP
...and gains status as a powerful observable for the phase boundary
Statistical hadronization of charm: method and inputs

• Thermal model calculation (grand canonical) \( T, \mu_B: \to n_{th}^X \)

\[ N_{cc}^{dir} = \frac{1}{2} g_c V (\sum_i n_{th}^D_i + n_{th}^\Lambda_i) + g_c^2 V (\sum_i n_{th}^\psi_i + n_{th}^\chi_i) \]

• \( N_{cc} \ll 1 \to \text{Canonical} \) (J. Cleymans, K. Redlich, E. Suhonen, Z. Phys. C51 (1991) 137):

\[ N_{cc}^{dir} = \frac{1}{2} g_c N_{oc}^{th} I_1 (g_c N_{oc}^{th}) I_0 (g_c N_{oc}^{th}) + g_c^2 N_{cc}^{th} \to g_c \text{ (charm fugacity)} \]

Outcome: \( N_D = g_c V n_{th}^D I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{th}^J/\psi \)

Inputs: \( T, \mu_B, \quad V_{\Delta y=1} = (dN_{ch}^{exp}/dy)/n_{ch}^{th}, \quad N_{cc}^{dir} \) (pQCD or exp.)

Minimal volume for QGP: \( V_{QGP}^{min} = 400 \text{ fm}^3 \)
Charmonium in the statistical hadronization model

\[ R_{AA}^{J/\psi} = \frac{dN_{AA}^{J/\psi}/dy}{N_{coll} \cdot dN_{pp}^{J/\psi}/dy} \]

- "suppression" at RHIC
- "enhancement" at the LHC

What is so different at LHC? (compared to RHIC)

\[ N_{J/\psi} \sim (N_{cc}^{dir})^2 \]

\( \sigma_{cc} : \sim 10x \), Volume: 2.2-3x

AA et al., PLB 652 (2007) 259

dthis was for full LHC energy ... but is a generic prediction of the model
Charmonium in the statistical hadronization model at LHC

\[ \frac{dN_{AA}/dy}{dN_{cc}/dy} \]

("proxy" for \( R_{AA} \))

- "enhancement" at the LHC

\[ N_{J/\psi} \sim (N_{cc}^{dir})^2 \]

canonical suppression (mostly) lifted, quadratic term dominant

it can be more dramatic at FHC

AA et al., in N. Armesto et al., “Last Call...”, JPG 35 (2008) 054001

dthis was for full LHC energy ... but is a generic prediction of the model
the generic prediction by the model is confirmed by data ALICE, PLB 734 (2014) 314 establishes charmonium as an ultimate observable of the phase boundary
Both model categories reproduce the data ... $d\sigma_{c\bar{c}}/dy$ values rather different:

midrapidity: Stat. Hadr.: 0.3-0.4 mb (will go up with incl. of more open charm states)
Transport: 0.5-0.75 mb (TAMU), 0.65-0.8 mb (Tsinghua)
Fractions primordial, (re)generated

TAMU transport model:
Zhao et al., NPA 859 (2011) 114 and priv. comm.

similar fractions in the Tsinghua model

NB: not only regeneration but also generation
**J/ψ vs. p_T - data**

midrapidity

forward rapidity

<table>
<thead>
<tr>
<th>p_T (GeV/c)</th>
<th>R_AA</th>
</tr>
</thead>
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<tr>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
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<tr>
<td>4</td>
<td>0.6</td>
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<tr>
<td>6</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- ALICE Preliminary, Pb-Pb, $\sqrt{s_{NN}}=2.76$ TeV, $|y|<0.8$, centrality 0-40%
- PHENIX, Au-Au, $\sqrt{s_{NN}}=0.2$ TeV, $|y|<0.35$, centrality 0-40%
- STAR, Au-Au, $\sqrt{s_{NN}}=0.2$ TeV, $|y|<1$, centrality 0-60%

Further support of (dominance of) a new production mechanism: "(re)generation" (re)generation in QGP or generation at chemical freeze-out (hadronization)

ALICE, PLB 734 (2014) 314 (& prelim., QM’14)
J/ψ Pb–Pb in context (p–Pb)

ALICE (Book, talk QM’14; C. Hadjidakis, arXiv:1405.1177)

midrapidity

forward rapidity

distinct differences between Pb–Pb and p–Pb, further support that low-$p_T$ J/ψ are from (re)generation (while high-$p_T$ is result of charm energy loss)

tantalizing implication for Pb–Pb: $R_{AA} > 1$ (at low $p_T$) if-more-charm

...cannot turn off shadowing, but means we may see this at the top LHC energy
J/ψ at RHIC, lower energies

$J/\psi \rightarrow \mu\mu, \ 1.2 < |y| < 2.2$

PHENIX, PRC 86 (2012) 064901

...not much "action"
**J/ψ at RHIC, lower energies**

seen already with the SPS data

...and “seen” in the stat. hadr. model

PHENIX, PRC 86 (2012) 064901

...not much “action”

AA et al., NPA 789 (2007) 334

...and in transport models (TAMU)
(after a fruitful journey) we stand at a crossroad...

...with two models describing the LHC (and RHIC) data well, with two rather different physics.

[one, simpler and well-constrained, the other with more capabilities ...but with more parameters]

While in the statistical model the hadronization is a process in which all quark flavors take part concurrently, in the kinetic (transport) model $J/\psi$ survives as a hadron in the hot medium of deconfined gluons and light quarks.

In the statistical model all charmonium states are generated exclusively at hadronization, while in the kinetic model only up to $2/3$ of the $J/\psi$ yield (LHC, central collisions) originates from deconfined $c$ and $\bar{c}$ quarks.

**Discriminating the two pictures implies providing an answer to fundamental questions related to the fate of hadrons in a hot deconfined medium.**

A precision ($\pm 10\%$) measurement of $\sigma_{c\bar{c}}$ in Pb-Pb (Au-Au) collisions needed within reach (?) with the upgraded detectors at the LHC and RHIC

...and data on other charmonium states is crucial
$\psi(2S)$ production at the LHC

$R = \frac{N_{\psi(2S)}^{\text{Pb-Pb}} / N_{J/\psi}^{\text{Pb-Pb}}}{N_{\psi(2S)}^{\text{pp}} / N_{J/\psi}^{\text{pp}}} = \frac{R_{\psi(2S)}^{\text{AA}}}{R_{J/\psi}^{\text{AA}}}$

$N$ - production yields

(light) “discrepancy” ALICE / CMS? mind diff. $p_T$, $y$ ranges

CMS (Moon, talk QM’14)
$\psi(2S)$ production at the LHC

$$R = \frac{N_{\psi(2S)}^{Pb-Pb}/N_{J/\psi}^{Pb-Pb}}{N_{pp}^{J/\psi}/N_{pp}^{\psi(2S)}} = \frac{R_{AA}^{\psi(2S)}}{R_{AA}^{J/\psi}}$$

at SPS: $R \approx 0.24$ ($p_T$-integrated)

...evidence against sequential dissociation?
$R < 1$ expected in both models, different magnitudes predicted ($p_T$-integrated)

Transport model: 
Zhao, Rapp, NPA 859 (2011) 114 and priv. comm.

Central Barrel: measurement possible only with upgrade (10 nb$^{-1}$) 
Muon Spectrometer: a first glimpse with baseline data (1 nb$^{-1}$), a real measurement only with upgrade

\[ R_{AA}^{\psi(2S)/J^{/}\psi} \]

symbols: expected ALICE data ($|y|<0.9$) 

pp ($N_{\text{coll}}$) scaling 
transport model ($\sqrt{s_{NN}}=2.76$ TeV) 
(dashed: shadowing) 
statistical model 

$N_{\text{part}}$
Charmonium ratios in p(d)-A collisions

PHENIX, PRL 111 (2013) 202301

ALICE, arXiv:1405.3796

abs. cross sect. depends on time spent in the nucleus

(MeGlinchey et al., PRC 87 (2013) 054910)

at the LHC, the strong \( \psi(2S) \) suppression in Pb-side remains puzzling indication for final-state effects?
Outlook for $J/\psi$

modest increase for 5.1 TeV
...due to modest increase in $\sigma c\bar{c}$
(slightly larger at forward $y$)
increasing trend vs. $N_{part}$ at FCC
Bottomonium at the LHC

interpreted as effect of (almost:) full
dissoc. of \( \Upsilon(2S) \), \( \Upsilon(3S) \), \( \chi_b \)

Transport models:
Emerick et al./TAMU, EPJA 48 (2012) 72

(re)gen. component small (\( \lesssim 10\% \))

CMS PbPb \( \sqrt{s_{\text{NN}}} = 2.76 \) TeV

\( R_{\text{AA}} \)

CMS PbPb \( \sqrt{s_{\text{NN}}} = 2.76 \) TeV, inclusive \( \Upsilon(1S) \), \( p_T > 4 \) GeV/c

<table>
<thead>
<tr>
<th>( N_{\text{part}} )</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{AA}} )</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td></td>
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</tr>
</tbody>
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CMS, PRL 109 (2012) 222301
ALICE, arXiv:1405.4493
Bottomonium at the LHC in SHM

\[ \frac{d\sigma_{b\bar{b}}}{dy} = 13.8 \, \mu b \] (MNR x0.8 shad.)

fair description by model

CMS, PRL 109 (2012) 222301
Bottomonium ratios

CMS data

- pp $\sqrt{s}=2.76$ TeV, $|y_{\text{cms}}|<1.93$
- p-Pb $\sqrt{s_{NN}}=5.02$ TeV, $|y_{\text{cms}}|<1.93$
- Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $|y_{\text{cms}}|<2.4$

statistical model describes central Pb–Pb data

thermal model (T=159 MeV)

CMS, JHEP 1404 (2014) 103
Bottomonium at the FCC in SHM

\[ \frac{d\sigma_{b\bar{b}}}{dy} = 109 \mu b \text{ (MNR x0.7 shad.)} \]

\[ V = 12000 \text{ fm}^3 \]

\[ Y(1S) \text{ in pp: 7 TeV data scaled by MNR factor of } \sigma_{b\bar{b}} \]

\[ \sqrt{s_{NN}}=40 \text{ TeV} \]

Y(1S), Statistical Hadronization Model
the story of quarkonium as a “golden probe” for QGP is rather intricate
(I think:) everybody agrees that we see (re)combination of charm quarks at LHC
...(in QGP and/or) at the phase boundary ...maybe similar at RHIC (SPS?)
model results dependent on $\sigma_{c\bar{c}}$, to be better constrained by measurements
interesting (sequential?) “disappearance” pattern in the bottom ($\Upsilon$) sector
do bottom quarks also thermalize at the LHC? (at RHIC?)
will $\Upsilon$ add more weight to the phase boundary?
a wealth of data (and puzzling too) in d-Au (RHIC) and p-Pb (LHC) awaits
better understanding

while measurements at the LHC at 5.1 TeV are eagerly awaited
...strong bet: $R_{AA}^{J/\psi}$ will increase
Backup slides
Charmonium data at RHIC and the LHC

midrapidity

forward rapidity

\[ \frac{dN_{ch}}{d\eta} \sim \varepsilon \]
**J/ψ** production relative to charm

...the most "solid" observable ...with similar features as $R_{AA}$

![Graph showing J/ψ production relative to charm](image)

- similar values at RHIC and SPS
  - ...with differences in fine details
  - ...determined by canonical suppression of open charm
    - same with $\Upsilon$ at RHIC and LHC?
- enhancement-like at LHC
  - can. suppr. lifted, quadratic term dominant

AA, PBM, JS, NPA 789 (2007) 334
J/$\psi$ flow

ALICE, PRL 111 (2013) 162301

CMS (Moon, QM’14)

further support of production in QGP or at chemical freeze-out at the LHC
(requiring thermalization of $c$, $\bar{c}$ and generically leading to flow)

Recall: non-zero $v_2$ was measured at SPS (“leakage effect”)
...the RHIC case (STAR, $v_2 \sim 0$) remains open ...upcoming data will settle it
model reproduces data (PHENIX, nucl-ex/0611020) very well (pQCD $\sigma_{c\bar{c}}$)

direct indication of $J/\psi$ generation at hadronization (enhanced at $y=0$)

(constant $R_{AA}$ expected within Debye screening model)

PLB 652 (2007) 259
$J/\psi$ at RHIC: effect of shadowing

Au+Au 0-20% ($N_{\text{part}}$=280)

- $\sigma_{cc}$: pQCD FONLL
- $\sigma_{cc}$: PHENIX
- +shadowing(dAu)

Au+Au 20-40% ($N_{\text{part}}$=140)

model describes data with PHENIX $\sigma_{\bar{c}c}$ (lower error plotted)
The “null hypothesis”

Data in pp(A) collisions...is far from thermalized (model is for AA)...

...while a thermal value is reached in central PbPb (NA50, SPS)
The “null hypothesis” for bottomonium

Relative cross section

Statistical model

bottomium in pp(A) collisions

...is far from thermalized (model is for AA)

...will we find a thermal value at LHC?
Bottomonium in p–Pb collisions

\[ R_{p\text{Pb}} = \frac{N_{p\text{Pb}}}{N_{\text{NN}}} \]

where \( s_{\text{NN}} = 5 \text{ TeV} \)

LHCb, JHEP 1407 (2014) 094