Quarkonia

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1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.

2) Gluons hold quarks together to form hadrons:

3) Gluons and quarks, or partons, typically exist in a color singlet state: confinement.
Time Scales

- **QGP life time**
  \[ 10 \text{ fm/c} \approx 3 \times 10^{-23} \text{ s} \]

- **thermalization time**
  \[ 0.2 \text{ fm/c} \approx 7 \times 10^{-25} \text{ s} \]

- **formation time**
  (e.g. charm quark):
  \[ \frac{1}{2m_c} = 0.08 \text{ fm/c} \approx 3 \times 10^{-25} \text{ s} \]

- **collision time**
  \[ \frac{2R}{\gamma} = 0.005 \text{ fm/c} \approx 2 \times 10^{-26} \text{ s} \]
Where does all the charm go?

- Total charm cross section: open-charmed hadrons, e.g. $D^0$, $D^+$, $D^{*+}$, $\Lambda_c$, ... and $c, b \rightarrow e(\mu) + X$
- Quarkonia, e.g. $J/\psi$ carries $\approx 1\%$ of total charm
Outline

• Introduction
• Charmonium production
• Bottomonium production
• Summary
ALICE is designed for

- Highest multiplicities $dN/d\eta$ up to 6000
- Excellent tracking & particle identification down to lowest momentum $\sim 100$ MeV/c
Discovery of charmonium

\( J: \) AGS at Brookhaven Lab., NY
\( p + \text{Be} \rightarrow \mu\mu \)

\( \psi: \) SPEAR at SLAC, CA
\( e^+ + e^- \rightarrow \text{hadrons} \)

\( m_{J/\psi} = 3.1 \text{ GeV}, J^{PC} = 1^- \text{ states} \)

Published back-to-back:

Nobel Prize 1976 for Samuel Ting and Burton Richter

Predicted by Sheldon Glashow and James Bjorken
Charmonium (c-cbar)

- Bound state of charm- and anti-charm quark
- Hidden-charm meson
- $m_{J/\psi} = 3.1$ GeV,
  $r_{J/\psi} = 0.45$ fm,
  $J^p = 1^-$ states

- $\Psi'$: radial excitation, $\psi(2s)$

Plot: M.B. Voloshin,
Time scales of charm production

- formation time of charm quark:
  \( \frac{1}{2}m_c = 0.08 \text{ fm}/c \)

- thermalization time:
  \( 0.2 \text{ fm}/c \)

- to build up wavefunction of J/\( \psi \) takes typically \( 1\text{ fm}/c \)

\( \rightarrow \) At LHC energies, QGP formed before J/\( \psi \) can exist

\( \rightarrow \) J/\( \psi \) unbound in QGP, thus no melting of J/\( \psi \) (does not exist in the first place)

\( \rightarrow \) Generation of J/\( \psi \) at the phase boundary, i.e. at Tc
**J/ψ suppression: the original idea**


Color screening will prevent bound ccubar states, i.e. suppression of charmonium signals QGP formation

No J/Ψ if $\lambda_D < r_{J/ψ}$

Debye length $\lambda_D \sim 1/(g(T) T$, so J/ψ is thermometer

Thermal picture: $n_{\text{partons}} = 5.2 \ T^3$ for 3 flavors

For $T = 500\text{MeV}$, $n_{\text{partons}} = 84/\text{fm}^3$

Mean separation $r = 0.2\text{fm} < r_{J/ψ}$

Dynamical picture: $J/ψ \rightarrow g + c + \bar{c}bar$
Debye Screening and Quarkonia

These quarks effectively cannot “see” each other!

RBC Bielefeld group, hep-lat/0610041.
Suppose $J/\psi$ does not melt
→ $R_{AA}$ should saturate > 0.6
→ no more feeding from $\chi_c$ and $\psi'$ → $J/\psi + X$
Quarkonia as a Thermometer

- Expect melting of bottomonium $(b\bar{b})$ at $T_{\text{deconfined}} \approx 2T_c$
- Expect melting of charmonium $(c\bar{c})$ at $T_{\text{deconfined}} \approx 1.2T_c$
- Absolute numbers model-dependent

B. $\psi'$ to J/ψ ratio

$m_{J/\psi} = 3.1$ GeV, $m_{\psi'} = 3.6$ GeV, look up $K_2(m/Tch)$

Ratio = 3%
Charmonium production

- In central Pb+Pb collisions at top SPS energy:
- $J/\psi'$ to $J/\psi$ ratio approaches thermal limit
- Indicates kinetic equilibration of charm
**J/ψ (charm-anticharm) Production**

- **Low energy (SPS):**
  - screening of J/ψ
  - ⇒ suppression

- **High energy (LHC):**
  - generation at phase boundary
  - ⇒ enhancement

- additional production mechanism at high-energy

- fingerprint of de-confinement

Some remarks

- number of charm quarks conserved throughout collision
- charm quarks are only produced in early stage
- No annihilation of charm quarks
- thermal production of charm unlikely: $\sim \exp(-2m_c/T), T << m_c$
- thus, charm is only re-shuffled amongst charmed hadrons
- effects of statistical hadronization of charm beyond current experimental sensitivity for open charmed hadrons (99% of all charm)
- effects sizeable for charmonium (1% of all charm)
Charmonium detection

\[ \jpsi \rightarrow e^+ + e^- \text{ (BR = 6\%)} \]  doable, also with trigger
\[ \jpsi \rightarrow \mu^+ + \mu^- \text{ (BR = 6\%)} \]  doable, also with trigger

\[ \psi' \rightarrow e^+ + e^- \text{ (BR = 0.8\%)} \]  lower rate, otherwise same as above
\[ \psi' \rightarrow \mu^+ + \mu^- \text{ (BR = 0.8\%)} \]  lower rate, otherwise same as above

\[ \chi_{c1} \rightarrow \jpsi + \gamma \text{ (BR = 34\%)} \]  hard, needs detection of soft photon
\[ \chi_{c2} \rightarrow \jpsi + \gamma \text{ (BR = 20\%)} \]  hard, needs detection of soft photon

\[ \eta_c \rightarrow \gamma + \gamma \text{ (BR = 1.8 \times 10^{-4})} \]  a real challenge (!)

→ Need **dileptons** to address **charmonium** production

→ Similar arguments hold for **bottomonium** \( \Upsilon(1), \Upsilon(2s), \Upsilon(3s) \)
Dimuons from CMS at LHC

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
$\Upsilon(1,2,3S)$

$\rho, \omega, \phi$  
$\psi(2S)$  

$L_{\text{int}} (\text{PbPb}) = 147 \mu b^{-1}$

$p_T^{\mu} > 4$ GeV/c

$E_{\text{ev}} (\text{GeV})$

$m_{\mu\mu}$ (GeV/c$^2$)
Statistical Hadronization of Charm

• up to 100 charm quark pairs in a single Pb+Pb collision at LHC

• generation of $J/\psi$ from deconfined quarks

• depends on total number of charm quarks

$N_{J/\psi} \sim (N_{ccbar})^2$

→ **Suppression** at RHIC

→ **Enhancement** at LHC

**Prompt J/ψ and from B → J/ψ + X**

- **disentangle prompt from secondary production by proper decay length (exponential decay of J/ψ from B)**
- **tag B-meson production**
Comparison to other hadrons

- Mass ordering in $R_{AA}$?
  - $J/\psi \leftrightarrow B$ (upper)
  - $D$ (middle)
  - $\pi$ (lower)

- $\gamma, W, Z$-bosons:
  - $R_{AA} \approx 1$ (!)
  - Checks normalization, does not probe the medium

ALICE, arXiv:1203.2160 [nucl-ex],
Sequential $\Upsilon$ suppression

Observation of sequential suppression of $\Upsilon$ family

When compared to pp collisions
Quarkonium-thermometer

Apparent hierarchy in $R_{AA}$ of different quarkonium states

However: $J/\psi$ from CMS are from high-$p_T > 6.5$ GeV/c

Not necessarily equilibrated in QGP
LHC versus RHIC energies

Enhancement at LHC

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

Suppression at RHIC

What is different?

Charm production at LHC is 10x RHIC
ALICE versus CMS at LHC

- charmonium less suppressed at low momentum (ALICE)

or (in other words)

- More generation in the bulk (at low $p_T$)

- suppresion at high-$p_T$ likely due to energy loss (as for D-mesons)
Lesson learnt

• Quarkonia (charmonium and bottomonium) and their production are unique probes of QGP

• Story has evolved over the last 30 years and is rather intricate

• $\Upsilon$ family apparently shows sequential melting with more strongly bound $\Upsilon(1)$ less suppressed than $\Upsilon(2s)$

• $J/\psi$ at high momentum shows suppression similar to open charmed hadrons (energy loss)

• $J/\psi$ shows effects of generation at the phase boundary due to statistical hadronization of charm at low momentum (bulk)

→ Harbinger of de–confinement