Charmonium modification in the quark-gluon plasma

LHCP 2023
Large Hadron Collider Physics Conference
Belgrade, 22-26 May 2023

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on behalf of the ALICE, ATLAS, CMS and LHCb collaborations
Outline

• Probing the QGP with charmonia
• Charmonium in heavy-ion collisions
  • Nuclear modification factor
  • Elliptic and triangular flow
  • J/ψ polarisation wrt Pb-Pb event plane
  • Coherent J/ψ photoproduction with nuclear overlap
  • Exotic charmonium χc1(3872) state

Selection of final/new results from ALICE, ATLAS, CMS and LHCb
Probing the QGP with charmonia

Charmonia
- Bound states of $c$ and $\bar{c}$
- Stable and tightly bound
- Produced in the initial hard partonic collisions in the early stage of the collisions ($\tau \approx 1/m_c$): charmonia experience the whole space-time evolution of the formed medium in heavy-ion collisions

Feed-down and non-prompt charmonia
- Prompt $J/\psi = \text{direct } J/\psi + \text{J}/\psi$ from excited states ($\chi_c, \psi(2S)$)

prompt $J/\psi$ in pp at LHC $\sim 80\%$ direct $J/\psi + 14\% \chi_c \rightarrow J/\psi + 6\% \psi(2S) \rightarrow J/\psi$

$Lansberg \text{ Phys.Rep.889 (2020) 1}$
- Inclusive $J/\psi (\psi(2S)) = \text{prompt } J/\psi (\psi(2S)) + J/\psi (\psi(2S))$ from b-hadron decays

<table>
<thead>
<tr>
<th>state</th>
<th>$\eta_c$</th>
<th>$J/\psi$</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$\psi'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass [GeV]</td>
<td>2.98</td>
<td>3.10</td>
<td>3.42</td>
<td>3.51</td>
<td>3.56</td>
<td>3.69</td>
</tr>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.75</td>
<td>0.64</td>
<td>0.32</td>
<td>0.22</td>
<td>0.18</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Probing the QGP with charmonia

From dissociation...
- At $T \gg 0$, high density of colour charge in the medium induces Debye screening
- At $T > T_D$, melting of quarkonia
- Since charmonia ($J/\psi$, $\psi(2S)$, …) have different binding energy
  $\rightarrow$ sequential suppression of charmonium and bottomonium states
  $\rightarrow$ quarkonium as a QGP thermometer

Matsui, Satz  PLB178(1986)
Rothkopf  Phys.Rept.858 (2020) 1
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... to regeneration…
- Total charm cross-section increases with energy
- $c$ and $\bar{c}$ combination in the QGP or at the phase boundary
  → regeneration of charmonia
  ➞ production enhancement
  ➞ evidence of thermalization of charm quarks
- regeneration delayed for loosely bound states (such as $\psi(2S)$)

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... and energy loss
- at large $p_T$, gluons can fragment into quarkonia → gluon energy loss in the QGP: suppression similar for all particles

References:
- Matsui, Satz, PLB178(1986)
- Rothkopf, Phys.Rept.858 (2020) 1
- Braun-Munzinger, Stachel PLB490(2000)
- Thews et al. PRC62(2000)
- Arleo PRL119 (2017) 062302
Charmonium measurements in heavy-ions at the LHC

**ALICE**
- midrapidity region with dielectron decay channel
- forward-rapidity region with dimuons

**ATLAS and CMS**
- midrapidity region with dimuons

**LHCb**
- forward-rapidity region with dimuons

**Complementary measurements**!

**LHC Pb-Pb collisions**
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ (Run 1), **5.02 (Run 2)**, 5.36 (Run 3/4) TeV
Inclusive J/ψ production

\[ R_{AA} = \frac{d^2 N^{AA}/dp_T dy}{\langle N_{coll} \rangle \cdot d^2 N^{pp}/dp_T dy} \]

- \( R_{AA} = 1 \): no modification
- \( R_{AA} > 1 \): enhancement
- \( R_{AA} < 1 \): suppression

• Less suppression at low \( p_T \) and at midrapidity: expected behaviour from J/ψ recombination
• Large suppression at large \( p_T \) with no rapidity dependence: interplay of dissociation and energy loss
Model comparison

- Good agreement with models:
  - full \( p_T/y \) ranges: transport models (regeneration, dissociation)
  - low \( p_T \): statistical hadronization model (SHMc - regeneration)
  - high \( p_T \): energy loss model
  - Large model uncertainty at low \( p_T \) from \( \sigma_{c\bar{c}} \) in Pb-Pb: need to constrain/measure it!

Models:
- Zhuang et al., PRC89 (2014) 054911
- Andronic et al., PLB797 (2019) 134836
- Arleo, PRL119 (2017) 062302
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- Large model uncertainty at low \( p_T \) from \( \sigma_{\text{cc}} \) in Pb-Pb: need to constrain/measure it!
- \( J/\psi / D \) ratio provides a tight constraint to models: SHMc model gives a good description of the centrality dependence of the ratio
Prompt J/ψ production

Separation of prompt and non-prompt J/ψ with proper decay time/length

\[ f_B = \text{non-prompt / inclusive} \]

- Non-prompt J/ψ fraction \( f_B \): increasing with \( p_T \) and lower for most central collisions
Prompt $J/\psi$ production

Separation of prompt and non-prompt $J/\psi$ with proper decay time/length

\[ f_B = \text{non-prompt / inclusive} \]

- Non-prompt $J/\psi$ fraction $f_B$: increasing with $p_T$ and lower for most central collisions
- Complementary $p_T$ ranges between ALICE, ATLAS and CMS for $R_{AA}$ of prompt $J/\psi$:
  - good agreement in overlapping region
  - almost no suppression at low $p_T$ as expected from regeneration mechanism
  - slight increase of $R_{AA}$ with $p_T$ as expected from energy loss mechanism

**Models:**
- Vitev et al., PLB778 (2018) 384
- Andronic et al., PLB797 (2019) 134836

**Graphs:**
- ALICE Preliminary
- $f_B$ vs. $p_T$ (GeV/c)
- $R_{AA}$ vs. $p_T$ (GeV/c)
ψ(2S) more suppressed than the J/ψ by a factor 2 (lower binding energy for ψ(2S))

- Similar dependence vs $N_{\text{part}}$ and $p_T$ for J/ψ and ψ(2S) with less suppression at low $p_T$ as expected from regeneration mechanism
- Strong ψ(2S) suppression persists up to $p_T = 30$ GeV/c
Elliptic and triangular flow of charmonia

- Another observable: azimuthal distribution of particles wrt the reaction plane
- Sensitive to initial collision asymmetry and event-by-event fluctuations
- Path length dependence at high $p_T$: charmonia expected to be more suppressed in longer path directions

\[
\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)].
\]

Fourier distribution

- $n = 2$: elliptic flow $v_2$
- $n = 3$: triangular flow $v_3$
- $\ldots$
Elliptic and triangular flow of charmonia

- Large $J/\psi$ $v_2$ up to $p_T = 50$ GeV/c:
  - low $p_T$: indication of collective flow behaviour of charm quarks
  - high $p_T$: path length dependence
- First indication of prompt $\psi(2S)$ $v_2 >$ prompt $J/\psi$ $v_2$ that may be linked to different hadronization time in the regeneration picture
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  - Prompt $J/\psi, \psi(2S) v_3$ consistent with zero at high $p_T$
Polarisation wrt Pb-Pb event plane

- Large magnetic field ($\vec{B}$) and angular momentum ($\vec{L}$) produced in the early stage of the QGP formation, perpendicular to the reaction plane → can influence the polarisation of quarkonia
- $B \sim 10^{14}$ T with short live time (1 fm/c)  \( \text{Kharzeev et al., NPA803 (2008)} \)
- $L$ highest in semi-central collisions, very large QGP velocity, with an effect on the system evolution up to freeze-out  \( \text{Becattini et al., PRC77 (2008) 024906} \)
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- $L$ highest in semi-central collisions, very large QGP velocity, with an effect on the system evolution up to freeze-out \cite{Becattini_2008}
- Polarisation of $J/\psi$ extracted along the axis perpendicular to the reaction plane

$$W(\theta) \propto \frac{1}{3 + \lambda_\theta} \left(1 + \lambda_\theta \cos^2 \theta\right)$$
Polarisation wrt Pb-Pb event plane

- Large magnetic field ($B$) and angular momentum ($L$) produced in the early stage of the QGP formation, perpendicular to the reaction plane, can influence the polarisation of quarkonia

- $B \sim 10^{14} \text{T}$ with short live time ($1 \text{ fm/c}$)

- $L$ highest in semi-central collisions, very large QGP velocity, with an effect on the system evolution up to freeze-out

- First $J/\psi$ measurement wrt event plane: small but significant transverse polarisation at low $p_T$ ($3.9\sigma$ effect for semi-central events and $p_T \sim 3 \text{ GeV/c}$)

- Spin alignment observed for light vector mesons ($K^*0$ and $\phi$) at midrapidity and low $p_T$: common origin? [ALICE, PRL125 (2020) 012301]

\[ W(\theta) \propto \frac{1}{3 + \lambda_\theta} \left( 1 + \lambda_\theta \cos^2 \theta \right) \]
Coherent $J/\psi$ photoproduction with nuclear overlap

- Strong electromagnetic field from Pb nuclei: photoproduction of vector mesons with very low $p_T (< 500 \text{ MeV})$
- Coherent production when the photon couples coherently with the target nucleus
- Processes well studied at LHC in ultra-peripheral Pb-Pb collisions (UPC) when the incoming nuclei do not overlap: see talk by J.G. Contreras

Coherent $J/\psi$ photoproduction also measured with nuclear overlap in peripheral collisions → theoretical challenges:
- does coherence condition survive for a broken nucleus?
- do only spectator nucleons participate to coherence?
- can this process be used as a probe of charmonium color screening in the QGP?
Coherent J/ψ photoproduction with nuclear overlap

Models:
- GG-hs: J. Cepila et al., PRC 97 (2018) 024901
- VDM: M. Klusek-Gawenda et al., PLB. 790 (2019) 339
- Zha et al., PRC99 (2019) 061901

- Cross section measured at forward and midrapidity: more than 5σ significance down to semi-central (30-50%) collisions at forward rapidity

\[ \text{ALICE, arXiv:2204.10684} \]
Coherent J/ψ photoproduction with nuclear overlap

- Cross section measured at forward and midrapidity: more than 5σ significance down to semi-central (30-50%) collisions at forward rapidity
- No centrality dependence (once normalised by the centrality bin width ΔC) of the cross section: no evidence of variation from nuclear overlap or medium effects

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ALICE, arXiv:2204.10684
Exotic charmonium $\chi_{c1}(3872)$ state

- $\chi_{c1}(3872)$: D-D* molecule or tetraquark? See talk by A. Rakotozafindrabe
- In heavy-ion, produced only at the hadronization stage? Regeneration for loosely bound states delayed with respect to compact tetraquarks
  
  \[ \text{Yield ratio: } \rho = \frac{N_{\chi(3872)\rightarrow J/\psi \pi \pi}^{\text{corr}}}{N_{\psi(2S)\rightarrow J/\psi \pi \pi}^{\text{corr}}} \]

- Evidence of $\chi_{c1}(3872)$ in Pb-Pb collisions
- Yield ratio enhanced in Pb-Pb wrt pp ($\rho_{\text{pp}} \sim 0.1$)
- Competing processes: regeneration vs suppression. These two processes can explain the $\chi_{c1}(3872)$ production dependence with system size.
Summary and outlook

- LHC experiments probe the quark gluon plasma formed in heavy-ion collisions with charmonium production

- Charmonium production measurements in heavy-ion collisions
  - Nuclear modification factor, $R_{AA}$
    - low $p_T$: $J/\psi$ and $\psi(2S)$ less suppressed at low $p_T$ as expected from regeneration mechanism
    - mid and high $p_T$: large suppression as an interplay between dissociation and energy loss
  - $\psi(2S)$ 2x more suppressed than $J/\psi$

- Elliptic and triangular flow
  - large $J/\psi$ $v_2$ and indication of larger $\psi(2S)$ $v_2$
  - $J/\psi$, $\psi(2S)$ $v_3$ consistent with zero at high $p_T$

- Polarisation wrt event plane
  - small but significant $J/\psi$ transverse polarisation at low $p_T$: effect from large $\vec{B}$ and $\vec{L}$ produced in the early stage?
  - Coherent $J/\psi$ $\gamma$-production: no dependence with centrality of the measured cross section within uncertainties
  - Evidence of exotic charmonium $\chi_{c1}(3872)$ in Pb-Pb with yield ratio to $\psi(2S)$ enhanced wrt pp

- LHC experiment upgrades for Run3/4 and forthcoming Pb-Pb run in fall 2023!
  - New detectors and higher rate capabilities
  - Stay tuned!
backup slides
Inclusive J/ψ production

ALICE arXiv:2303.13361

**Figure 1:**
- **Left panel:** $R_{AA}$ vs. $p_T$ (GeV/c) for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, with $|y| < 0.9$.
  - Data points for 0–10% and 30–50% centrality.

- **Right panel:** $R_{AA}$ vs. $p_T$ (GeV/c) for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, with $2.5 < y < 4$.
  - Data points for 0–20%, 20–40%, and 40–90% centrality.
J/ψ polarisation in Pb-Pb collisions

- Polarisation provides information complementary to the yield production
- Important per se for detector effect correction
- Polarisation measured in the helicity and collins-super frame

- Polarisation compatible with zero (2 sigma from 0 at low $p_T$) and with ALICE pp measurements: no or small modification of the polarisation with the medium

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ALI-PUB-490215

Cynthia Hadjidakis  LHCP2023  May 2023
Jet fragmentation containing a prompt J/ψ
$\chi_{c1}(3872)$

- CMS Inclusive
- $\psi(2S)$
- $X(3872)$
- $\sigma_{X(3872)} = 4.7$ MeV/c$^2$

- $15 < p_T < 50$ GeV/c
- $|y| < 1.6$ Cent. 0-90%

- $b$-enriched ($lxy > 0.1$ mm)
- data
- total fit
- background

- LHCb
- Prompt + $b$ decays

- Comover Interaction Model, Esposito et al.
- Molecule (coalescence), Compact tetraquark, Molecule (geometric)

- $\sigma_{LHCb}$, $\frac{B_{X(3872) \rightarrow \psi(2S) J/\psi \pi}}{BR_{J/\psi \pi}}$

- $N_{VELO}$ tracks

- 1.7 nb$^{-1}$ (PbPb 5.02 TeV)
Coherent $J/\psi$ photoproduction with nuclear overlap

\[ R_{AA}, \text{Pb-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

$J/\psi \to \mu^+\mu^-$, $2.5 < y < 4$

- $p_T < 0.3 \text{ GeV/c}$
- $0.3 < p_T < 1 \text{ GeV/c}$
- $1 < p_T < 2 \text{ GeV/c}$

Data | Model
--- | ---

ALICE, Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
Centrality 50-70%
Global syst. uncertainty: 9.2%

$J/\psi \to e^+e^-$, $|y| < 0.9$
Upper limit 95% C.L.


ALICE Preliminary

$Pb-Pb$, $\sqrt{s_{NN}} = 5.02$ TeV
Centrality 70-90%
Global syst. uncertainty: 8.6%

$J/\psi \to e^+e^-$, $|y| < 0.9$
Upper limit 95% C.L.

Quark-gluon plasma in heavy-ion collisions

- Nuclear matter at high temperature and high density = Quark Gluon Plasma (QGP)
- From lattice QCD: phase transition near $T_c = 170$ MeV ($\varepsilon_c = 1$ GeV/fm$^3$)
- At LHC energies: most particles produced during the collisions $\rightarrow$ very low net baryon density
- Heavy ion collision experiments: characterize the QGP phase
- At large energy: large, hot, dense, long life-time plasma

$\tau = 20$ fm/c  
Kinetical freeze-out
Chemical freeze-out

$\tau = 10$ fm/c  $T < T_c$  
Hadron gas

$\tau = 1$ fm/c  $T > T_c$  
Thermalized QGP

$\tau = 0$  
Heavy-ion collision

$LHC$ size and time numbers
$1$ fm/c $\sim 3 \times 10^{-24}$ s
Collision geometry: few definitions

Centrality of the collisions: overlap of two nuclei

semi-central collision

central collision

Impact parameter of the collision: $b$

Number of participants nucleons: $N_{\text{part}}$

Number of binary collisions: $N_{\text{coll}}$

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{part}}$</th>
<th>$N_{\text{coll}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb cent.</td>
<td>360</td>
<td>1500</td>
</tr>
<tr>
<td>p-Pb cent.</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

$N_{\text{part}} = 2$, $N_{\text{coll}} = 1$

$N_{\text{part}} = 5$, $N_{\text{coll}} = 6$
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central collision

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Number of binary collisions: $N_{\text{coll}}$

Event centrality determination

- Cannot measure $b$, $N_{\text{part}}$, $N_{\text{coll}}$ directly
- Multiplicity measurements with forward or central detectors (charged particles multiplicity - $\pi$, $K$, $p$...)
- Spectator neutrons, ...
- Use Glauber model to map the measured multiplicities in A-A collisions to $b$, $N_{\text{part}}$ and $N_{\text{coll}}$
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