Challenges in quarkonium and exotic-state production in small systems

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Small systems

Old paradigm:
- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as QCD baseline appears no longer sensible

Discovery of correlations –ridge, flow- in small systems pA & pp at high multiplicity
- Smooth continuation of heavy ion phenomena to small systems
- Small systems as pA and pp show QGP-like features

Two different explanations remain today:
- initial state: quantum correlations as calculated by CGC
- final state: with (hydrodynamics) or without equilibration

We should examine a new paradigm, where the physics underlying collective signals can be the same in all high energy reactions, from pp to central AA, depending on energy density/mult...
The models, which are also in agreement with the results at 2.76 TeV [12, 50], predict increases. For the model of Du, He, and Rapp, the temperatures are in the range shown in Fig. 6. The medium temperature. The temperatures reported in the model of Krouppa and Strickland results for the

Since the suppression is expected to be larger for higher temperatures in the medium, the different phenomena affecting quarkonium states that is yet to be fully understood [49].

The centrality-integrated results for the

at 5.02 TeV is larger by a factor of

The centrality-integrated Figure 7 compares centrality-integrated

The excited state). For the

of Du, He, and Rapp uses a kinetic-rate equation to simulate the time evolution of bottomo-

fireball evolution. Within the current theoretical and experimental uncertainties, both models

and the initial momentum-space anisotropy. The initial temperature is determined by requir-

temperature-dependent binding energies, and a lattice-QCD-based equation of state for the

nium abundances in ultra-relativistic heavy ion collisions. It considers medium effects with

Figure 5: Nuclear modification factors for the

Measuring quarkonium nuclear effects: the nuclear modification factor $R_{AA}$

\[ R_{AA} = \frac{d^2N^{pA}/dp_Td\eta}{N_{coll}d^2N^{pp}/dp_Td\eta} \]

- $R_{AA}<1$: suppression
- $R_{AA}=1$: no nuclear effects
- $R_{AA}>1$: enhancement

Original motivation to measure quarkonium in nuclear collisions (AA): Signal of QGP

Observable: $R_{AA}$ vs energy density

- The 3 upsilon states are suppressed with increasing centrality/energy density

\[ R_{AA}[\Upsilon(1S)] > R_{AA}[\Upsilon(2S)] > R_{AA}[\Upsilon(3S)] \]

$\Rightarrow$ Sequential melting
The models, which are also in agreement with the results at 2.76 TeV \cite{12, 50}, predict increases shown in Fig. 6 are the medium temperature. The temperatures reported in the model of Krouppa and Strickland results for the since the suppression is expected to be larger for higher temperatures in the medium, the different phenomena affecting quarkonium states that is yet to be fully understood \cite{49}. The centrality-integrated results for the studied kinematic regions. This suggests a measured correlated and therefore removed, although the two at 5.02 TeV is larger by a factor of be compared with the result at 2.76 TeV, 0.453.

Nuclear modification factor $R_{AA}$

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Cross section ratio

CMS pp $\sqrt{s} = 2.76$ TeV

CMS PbPb $\sqrt{s_{NN}} = 5.02$ TeV

CMS pp $\sqrt{s} = 2.76$ TeV

CMS PbPb $\sqrt{s_{NN}} = 5.02$ TeV

$|\eta_{CM}|<1.93$

arXiv:1312.6300
The models, which are also in agreement with the results at 2.76 TeV \([12, 50]\), predict increases... 

For the model of Du, He, and Rapp, the temperatures are in the range shown in Fig. 6 are the medium temperature. The temperatures reported in the model of Krouppa and Strickland results for the...

Since the suppression is expected to be larger for higher temperatures in the medium, the different phenomena affecting quarkonium states that is yet to be fully understood \([49]\). The suppression is compared with the result at 2.76 TeV, 0.453...
...but the situation is by far much more complex

- There are other effects, not related to colour screening, that induce suppression of quarkonium states
- These effects are not all mutually exclusive
- They should be also taken into account in AA collisions
  the distinction of these effects is not straightforward, their factorization is not easily established

- **Modification of the gluon flux** *initial-state effect*
  - Nuclear PDF in nuclei: nPDF shadowing
  - Gluon saturation at low x: CGC

- **Parton propagation in medium** *initial/final effect*
  - Coherent energy loss

- **Quarkonium-medium interaction** *final-state effect*
  - Comover interaction/transport models
  - Nuclear break-up

- **Other QGP-like effects?**
Modification of the gluon flux: Nuclear modification of PDFs

- Modification of the gluon flux: initial-state effect

Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

\[ J/\psi \] suppression or enhancement as a function of the parton momentum fraction \( x \) in the nucleon

- Nuclear PDF in nuclei: nPDF shadowing

![Graph showing nuclear modification of PDFs](image-url)
Modification of the gluon flux: Nuclear modification of PDFs

- Modification of the gluon flux: initial-state effect
- Nuclear PDF in nuclei: nPDF shadowing

Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

$\Rightarrow$ J/ψ suppression or enhancement as a function of the parton momentum fraction $x$ in the nucleon

- It can explain the suppression at forward rapidity, the effect is around 1 at backward rapidity
- Roughly agrees with quarkonium ground-state data
- Issue: results very much widespread, applicability of reweighting?

Extra effect in the backward region?
Modification of the gluon flux: Nuclear modification of PDFs

- Modification of the gluon flux: initial-state effect

Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

\[ Y(1S) \text{ suppression or enhancement as a function of the parton momentum fraction } x \text{ in the nucleon} \]

- It can explain the suppression at forward rapidity, the effect is around 1 at backward rapidity
- Roughly agrees with quarkonium ground-state data
- Issue: results very much widespread, applicability of reweithing?
  
Extra effect in the backward region?

Warning (by JPL): The J.Lansberg et al curves are reweighted nPDF; this should be stated, and in fact I am not the first author...

EPPS16 are obtained after reweighting the corresponding nuclear PDF sets using LHC heavy-flavour data. Figure from Ref. [PLB 774 (2017) 159]

Figure 30: Comparison of the ALICE

\[ \text{p-Pb } \sqrt{s_{NN}} = 8.16 \text{ TeV} \]

ALICE inclusive J/\( \psi \)
LHCb prompt J/\( \psi \) (PLB 774 (2017) 159)
Modification of the gluon flux: Gluon saturation

- **Modification of the gluon flux**
  - Initial-state effect

Gluon saturation: Result of gluon recombination at small $x$ at LHC

$\Rightarrow$ $J/\psi$ suppression at forward rapidity (this effect does not apply in the backward rapidity region)

- CEM with improved geometry
  - Ducloue et al

- NRQCD: results depend on the CO channel mix, contribution of CS channel relatively small
  - Venugopalan et al

- **Issue:** Results can vary depending of the production mechanism
  - Shadowing & CGC are mutually exclusive

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**Gluon saturation at low x: CGC**

$$Q_{sA}^2 = A^{1/3} \times 0.2 \times \left( \frac{x_0}{x} \right)^{\lambda}, \quad \lambda \sim 0.2 \div 0.3 \quad x_0 = 0.01$$

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**Figure 30:** Comparison of the ALICE $\bar{p}$-Pb $\sqrt{s_{NN}} = 8.16$ TeV $p$-A

- ALICE inclusive $J/\psi$
- LHCb prompt $J/\psi$ (PLB 774 (2017) 159)
Parton propagation in medium: Coherent energy loss

\[ \Delta E = \int d\omega \omega \left| \frac{d}{d\omega} \right|_{\text{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q^2_T}}{m_T} E \]

- Parton propagation in medium \textit{initial}/\textit{final} effect
  - Nuclear transverse momentum broadening of the heavy quark pair induces coherent gluon radiation \( \Rightarrow J/\psi \) & \( Y(1S) \) yield modification
  - Roughly agrees with quarkonium ground-state data
  - Issue: Impossible to discriminate from nPDF modification

**Coherent energy loss**

DY measurements could help

Extra effect in the backward region?
Quarkonium-medium interaction: final-state effect

- J/ψ shows stronger suppression at forward rapidity while compatible with 1 at backward rapidity.
- The pattern is consistent with initial- and final-state effect models
- ψ(2S) shows similar suppression in both intervals
- Cannot be described by only initial state effects
- Inclusion of final-state effects give a good description for both states
Data from RHIC & LHC

- Relative $\psi(2S)/J/\psi$ suppression in dAu collisions @ 200 GeV (PHENIX)
- Relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 5 & 8 TeV (ALICE & LHC)
- Relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 5 TeV (CMS & ATLAS)
- Relative $Y(nS)/Y(1S)$ suppression in pPb collisions @ 5 TeV & 8TeV (CMS & ATLAS & LHC)

- Initial-state effects – modification of nPDFs / coherent E loss- identical for the family
- Any difference among the states should be due to final-state effect
- At low $E$: the relative suppression can be explained by nuclear absorption $\sigma_{\text{breakup}} \propto r^2_{\text{meson}}$

At high $E$: too long formation times $t_f = \gamma \tau_f >> R \Rightarrow$ the quantum state does not matter!

A natural explanation would be a final-state effect acting over sufficiently long time

$\Rightarrow$ interaction with a comoving medium through a transport equation
**Excited states: Comover interaction**

- In a comover model: suppression from scatterings of the nascent $Q$ with comoving medium of partonic/hadronic origin
  
  *Gavin, Vogt, Capella, Armesto, EGF, Tywoniuk...*

- Rate equation governing the charmonium density:

$$
\frac{d \rho_{\psi}}{d \tau} (b, s, y) = -\sigma_{CO-\psi} \rho_{CO}(b, s, y) \rho_{\psi}(b, s, y)
$$

$\sigma_{CO-\psi}$ originally fitted from SPS data

- To get rid of initial-state effects: double ratio excited-over-ground state

- Going to a microscopic level:

$$
\sigma_{CO-Q}(E^{co}) = \sigma_{geo} \times \left(1 - \frac{E_{thr}}{E^{co}}\right)^n
$$

$\sigma_{geo} \sim \pi r_Q^2$,

$E_{thr} = 2M_Q - M_{Q\bar{Q}}$

$E^{co} = \sqrt{p^2 + m_{co}^2}$

$\mathcal{P}(E^{co}, T_{eff})$ Bose Einstein distr.

$$
\langle \sigma_{CO-Q} \rangle (T_{eff}, n) = \frac{\int_0^\infty dE^{co} \mathcal{P}(E^{co}, T_{eff}) \sigma_{CO-Q}(E^{co})}{\int_0^\infty dE^{co} \mathcal{P}(E^{co}, T_{eff})}
$$

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Excited states: Comover interaction

Transport model with final interactions [Du & Rapp (2015)]
“similar in spirit to comover suppression”

→ New results on $\psi(2S)$ confirm stronger suppression w.r.t. to $J/\psi$ in the Pb-going direction.

→ Final state effects are needed to reproduce the $\psi(2S)$ suppression.

Stronger suppression in the nucleus-going direction (higher mult) => CI improves agreement for the ground state in the backward region (initial nPDFs modification also included)

Soft color exchanges between $c\bar{c}$ & comovers at later stage

Ma, Venugopalan, Zhang, Watanabe (2018)
Measuring *nuclear-like* effects in pp: the observables

Relative multiplicity:

\[ \frac{N_{\text{ch}}}{\langle N_{\text{ch}} \rangle} \]

- Numerator characterises each event.
- Denominator is averaged over the full datasample.

Relative yields:

\[ \frac{N_{J/\psi}^i}{\langle N_{J/\psi} \rangle} \]

- Numerator quantifies the number of quarkonia in bin \( i \).
- Denominator gives the average number of quarkonia in the datasample.
Measuring *nuclear-like* effects in pp: the observables

Relative multiplicity:

$$\frac{dN_Q/dy}{\langle dN_Q/dy \rangle}$$

$$\frac{N_{ch}}{|\langle N_{ch} \rangle|}$$

Relative yields:

$$\frac{N_{J/\psi}^i}{\langle N_{J/\psi} \rangle}$$

The probability to produce the hard process scales with the mean multiplicity

The production is independent of the underlying event

Sarah Porteboeuf’s slide

$$\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$$
Quarkonium vs multiplicity

- **EPOS**: MPI via Pomeron exchange (initial) + hydrodynamic expansión (final) hydro on/off has small effect, hadronic cascade on/off has no effect
- **PYTHIA**: MPI, hard scatterings (initial) + color reconnection, string shoving (final)
- **CGC**: Gluon saturation (initial) => Impact on particle producción, reduction
- **Percolation**: String saturation (initial) => Reduction on the number of charged particle

**Initial state effects** play a fundamental role:

- **MPI** can introduce collectivity => Increase of hardness
- **Saturation** => Decrease on total multiplicities => Indirect increase of the hard probe (not affected by saturation)
  - Events at different energies with the same $p_{\text{strings}}$ or $Q_s$ are identical
  - The harder the probe, the stronger the difference

**Multiplicity and probe measured in the same rapidity interval (both mid rapidities)**
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  - Multiplicity and probe measured in the same rapidity interval (both mid rapidities)

\[
\frac{dN_{J/\psi}}{dy} \quad \text{vs} \quad dN_{ch}/dy
\]

- ALICE pp \( s = 13 \) TeV
- Inclusive J/\( \psi \), \( |y| < 0.9 \), \( p_T \) integrated
- SPD event selection
  - Data
  - PYTHIA 8.2

- Prompt J/\( \psi \)
  - CPP
  - EPOS3 (no hydro)
  - 3-Pomerons
  - CGC
  - Percolation

\( y = x \)

**ALICE** pp \( s = 13 \) TeV
- Inclusive J/\( \psi \), \( |y| < 0.9 \)
- SPD event selection
  - Data
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Challenges in quarkonium and exotic-state production in small systems
To get rid of initial-state effects: double ratio excited-over-ground state

- Initial-state effects cancel

- Final-state effects at play?
Studies of ground vs excited states can improve our understanding of the final-state effects consistent with a suppression of the excited $Y$ states at high charged-particle multiplicity.

Application of final state comover interaction to spectroscopy in pp collisions
Final remarks

- **Quarkonium ground states and open heavy mesons** $R_{pA}$ can be reasonably well described by *initial state effects*: nPDF modifications *or* CGC *and/or* coherent energy loss.

- In order to describe *excited states* $R_{pA}$, *final state effects* become mandatory: Botzmann eq to describe the interaction with the medium, not necessarily in thermal equilibrium.

- Clearly the extrapolated pA effects are significant and need to be understood for a proper interpretation of the AA results: *The effects that are at play in pA should be also taken into account in AA collisions*.

- **Collectivity effects** are also present in high-multiplicity pp collisions: *initial* or *final effects*? The similarity between the D and J/ψ suggests that this behaviour is most likely related to the production processes. Moreover, no significant energy dependence is observed, which agrees with saturation approach.

- **Final effects** are required to explain excited over ground state data also in pp high-multiplicity collisions.

- In more general terms, if equilibrium is no longer a requirement, this naturally explain why pp data on azimuthal correlations appears to be so similar to data obtained in AA collisions (hydro vs. non-hydro initial-state explanation) How far can we go in this direction?