Overview on hidden heavy flavour results

Roberta Arnaldi
INFN Torino (Italy)

The 18th International Conference on
Strangeness in Quark Matter (SQM 2019)
10-15 June 2019, Bari (Italy)
Outlook

Overview of most recent results on several quarkonium states

in different colliding systems:

- $\Upsilon(1S)$
- $\Upsilon(2S)$
- $\Upsilon(3S)$
- $J/\psi$
- $\psi(2S)$

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pp vacuum reference + pp physics

pA cold/(hot?) nuclear matter effects

AA hot matter effects

(almost to scale 😊)
Overview of most recent results on several quarkonium states

- $\Upsilon(1S)$
- $\Upsilon(2S)$
- $\Upsilon(3S)$
- $J/\psi$
- $\psi(2S)$

in different colliding systems:

- pp: vacuum reference + pp physics
- pA: cold/(hot?) nuclear matter effects
- AA: hot matter effects

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(almost to scale 😊)
Outlook

**RHIC:**
various collision systems are explored, scanning in energy

<table>
<thead>
<tr>
<th>Exp.</th>
<th>System</th>
<th>$\sqrt{s_{\text{NN}}}$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHENIX STAR</td>
<td>AuAu, CuCu, CuAu, UU</td>
<td>0.039 – 0.2</td>
</tr>
<tr>
<td></td>
<td>p-A, d-Au, p-Al, $^3$He-Au</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>pp</td>
<td>0.2-0.5</td>
</tr>
</tbody>
</table>

**LHC:**
results are complementary, due to different kinematic coverages

<table>
<thead>
<tr>
<th>Exp.</th>
<th>System</th>
<th>$\sqrt{s_{\text{NN}}}$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>PbPb, XeXe</td>
<td>2.76, 5.02, 5.44</td>
</tr>
<tr>
<td>ATLAS</td>
<td>pPb</td>
<td>5.02, 8.16</td>
</tr>
<tr>
<td>CMS</td>
<td>pp</td>
<td>2.76, 5, 7, 8, 13</td>
</tr>
<tr>
<td>LHCb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Credits

PHENIX
Marzia Rosati Mon 14.30

ATLAS
Martin Spousta Mon 15.30

STAR
Guanna Xie Mon 15.30
Te-Chuan Huang Thu 14.00

CMS
Ruslan Chistov Mon 17.00
Daniele Fasanella Tue 17.10
Xiao Wang Thu 16.30,
P. Pujahari Tue 11.00

ALICE
Andrea Rossi Mon 16.30
Minjung Kim Thu 14.40
Wadut Shaikh Thu 15.20

LHCb
Shanzhen Chen Mon 17.00
Hengne Li Thu 14.20

(main focus of my talk will be on the newest results presented in this conference)
New quarkonium results

pp
- production cross sections
- production vs. event activity
- production in jets

pA
- $R_{pA}$ studies for ground and excited states production
- $J/\psi$ elliptic flow

AA
- multi-differential $R_{AA}$ measurements
- new observables as
  - polarization
  - $\Upsilon$ elliptic flow

All the new RHIC and LHC measurements:
- extend the kinematic coverage reached so far
- have an improved precision

→ pp, pA and AA results represent a challenge for theory comparison
pp collisions

STAR, pp@200 - 500/510GeV
J/ψ precision measurement extending the $p_T$ coverage up to 20GeV/c
→ agreement with iCEM, NRQCD, CGC+NRQCD models (+FONNL) within uncertainties

ALICE pp@5, 13TeV
improved quarkonium cross sections with Run2 data
→ larger luminosity wrt Run1
→ increase pp reference precision for $R_{AA}$

→ improved references for pA and AA studies

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Onia production vs ev. activity

Study role of MPI in quarkonium production

Increase of J/ψ and γ yields with event activity observed at RHIC and LHC

→ Increase is:
  • weakly dependent on energy
  • stronger for high $p_T$
  • stronger than linear when no rapidity gap is present between quarkonium and multiplicity measurement
  • independent on quarkonium state

STAR $J/\psi$

STAR γ(1S)

ALICE

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Onia production vs event activity

Study role of MPI in quarkonium production

- EPOS3 and PYTHIA: include MPI
- Kopeliovich: high multiplicities reached via contribution of higher Fock states
- Percolation: mimic MPI via interactions of colour sources with finite spatial extension
- CGC saturation effects

Most predictions, based on different underlying processes, are in qualitative agreement with data

STAR, arXiv:1805.03745

ALICE, J/ψ

STAR, J/ψ

Ma et al, PRD98 (2018) 074025
Prompt $J/\psi$ production is studied in jets through the self-normalized $z$ distribution

$$z = \frac{p_{T,J/\psi}}{p_{T,\text{jet}}}$$

Prompt $J/\psi$ carry a small fraction of jet momentum

→ their production is accompanied by a large jet activity, much larger than the one predicted by PYTHIA8

Result is consistent with similar observation from LHCb in pp@13TeV (PRL118(2017)19,2001)
Cold Matter effects

Quarkonium production is affected by effects related to cold nuclear matter (CNM):

- nuclear parton shadowing/gluon saturation
- energy loss
- $c\bar{c}$ break-up in nuclear matter

addressed via pA collisions, to investigate

- role of the various CNM contributions, whose importance depends on kinematic and energy of the collisions
- size of CNM effects, fundamental to interpret quarkonium AA results
- presence of possible hot matter effects
J/ψ in pA collisions at RHIC

- J/ψ production in small systems now studied, also multi-differentially, in p-Al, p-Au, d-Au, ³He-Au
- limited CNM effects in p-Al data
- similar $R_{pA}$ increase vs $p_T$ in p-Au, d-Au, ³He-Au. No forward vs backward-γ difference?
- shadowing models predict $R_{pA}$ slightly higher than unity (at mid-γ)
- additional contribution on top of shadowing, as the cc break up in medium?
CNM effects affect J/ψ production mainly at forward-γ and low $p_T$

consistent results between experiments in similar kinematic range (LHCb, PLB774 (2017) 159)

fair agreement between data and models based on shadowing, CGC, energy loss

size of uncertainties (mainly shadowing) still limits a more quantitative comparison
RHIC:
Improved precision in p-Au, but a precise comparison with models is still difficult

LHC:
- suppression stronger at forward-\(\gamma\) and low \(p_T\)
- shadowing and energy loss models fairly describe data at forward-\(\gamma\) and mid-\(\gamma\), but slightly overestimate backward-\(\gamma\) \(R_{pA}\)?
Excited bottomonium states

Excited $\Upsilon$ states show a stronger suppression than $\Upsilon(1S)$ in $pPb$ wrt $pp$.

Final state effects might be needed to explain the observations, as for charmonium.
a significant non-zero $\nu_2$ is observed in high-multiplicity p-Pb

- size of $\nu_2$ similar to the one measured in PbPb
- however, common $\nu_2$ interpretation for PbPb, based on regeneration or path lengths effects doesn’t work in pPb
- models where the $\nu_2$ originates from final state effects (dissociation/regnation) in the fireball underestimate the data

[E. Chapon, Friday 12.00]
Hot Matter effects

the original idea:
quarkonium production suppressed via color screening in QGP

(T.Matsui,H.Satz, PLB178 (1986) 416)

Recombination
$q\bar{q}$ abundance increases with collision energy

<table>
<thead>
<tr>
<th>Central AA coll</th>
<th>$N_{cc}$ per ev.</th>
<th>$N_{bb}$ per ev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHIC, 200GeV</td>
<td>~10</td>
<td>-</td>
</tr>
<tr>
<td>LHC, 5.02 TeV</td>
<td>~115</td>
<td>~3</td>
</tr>
</tbody>
</table>

→ (re)combination at hadronization or in QGP enhances charmonium production
→ small contribution for bottomonium (also at LHC)


Sequential melting
differences in quarkonium binding energies lead to a sequential melting with increasing temperature

Digal, Petreci, Satz PRD 64(2001) 0940150

J/$\psi$ production probability vs. energy density

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Charmonium in AA

**Low $\rho_T$ $J/\psi$**

- PHENIX, 0.2TeV
- ALICE, 2.76TeV
- ALICE, 5.02TeV

**High $\rho_T$ $J/\psi$**

- CMS, 2.76TeV
- STAR, 0.2TeV

Stronger suppression at RHIC in central events, in spite of the larger LHC energy densities.

Suppression increases towards central events, being of similar size at RHIC and LHC energies.

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Models with suppression + regeneration mechanisms, with regeneration at play in the low $p_T$ region and at high energy, fairly describe the data.
Indication of a high $p_T$ rise, as for charged hadrons or D mesons

$\rightarrow$ weak regeneration expected, parton energy-loss at play?
Bottomonium in AA

Three $\Upsilon$ states with different sensitivity to the medium

limited recombination and no B feed-down (but large feed-down from excited states)

interesting for sequential suppression studies

Strong centrality suppression for all $\Upsilon(nS)$ (factor $\sim 2$ for $\Upsilon(1S)$, $\sim 9$ for $\Upsilon(2S)$)

- lower $R_{AA}$ values for excited states compatible with sequential suppression
- suppression of directly produced $\Upsilon(1S)$? Feed down contribution $\sim 30$
- models (almost all including suppression and regeneration) fairly describe the data
Bottomonium in AA

Models describing LHC results also describe RHIC ones

- Similar $\Upsilon(1S)$ suppression, within uncertainties, at RHIC and LHC → might imply weak or no suppression of direct $\Upsilon(1S)$ at LHC
- Excited states suppression is stronger at LHC
J/ψ elliptic flow

J/ψ from recombination should inherit the thermalized charm flow

J/ψ $v_2$ measurement over a broad $p_T$ range

- **Low $p_T$:** evidence for non-zero flow (ALICE, $7\sigma$ effect in $4<p_T<6$ GeV/$c$)
- **High $p_T$:** $v_2 \neq 0$ (ATLAS and CMS)

**Graph:**

- ATLAS, Prompt J/ψ, 5.02 TeV, $|y| < 2$, 0 - 60%
- ALICE, Inclusive J/ψ, 5.02 TeV, 2.5 < $y$ < 4, 20 - 40%
- CMS, Prompt J/ψ, 2.76 TeV, 1.6 < $|y|$ < 2.4, 10 - 60%
- CMS, Prompt J/ψ, 2.76 TeV, $|y| < 2.4$, 10 - 60%

ATLAS, EPJC 78 (2018) 784
CMS, EPJC 77 (2017) 252
J/ψ elliptic flow

J/ψ from recombination should inherit the thermalized charm flow

J/ψ $v_2$ measurement over a broad $p_T$ range

Comparison to models:

low $p_T$:
$\nu_2$ reproduced including a strong J/ψ regeneration component

high $p_T$:
energy loss path-length dependence plays a role, but $\nu_2$ still underestimated
First measurement of inclusive $J/\psi$ $\nu_3$

3.7$\sigma$ significance for a positive $\nu_3$ over the full $p_T$ range
First measurement of $\Upsilon(1S)$ elliptic flow in AA, based on 2015+2018 samples

- $\Upsilon(1S) v_2$ is consistent with zero over the full $p_T$ range, in 5-60% centrality
- $v_2$ is compatible with the small values predicted by theory models including (TAMU) or not (KSU) a regeneration contribution
- $J/\psi$ $v_2$ is 2.6$\sigma$ higher than the $\Upsilon(1S)$ one in 2<$p_T$<5 GeV/c → hint for a different production mechanisms in PbPb?
**J/ψ polarization**

First J/ψ polarization measurement in PbPb collisions

Polarization parameters are evaluated from the angular distribution of decay muons in the quarkonium rest frame:

\[
W(\cos \theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \left( 1 + \lambda_\psi \cos^2 \theta + \lambda_\psi \sin^2 \theta \cos 2\phi + \lambda_{\psi\psi} \sin 2\theta \cos \phi \right)
\]

- **All J/ψ polarization parameters are consistent with zero**
- Result compatible with a first measurement at SPS energies (NA60, InIn@\(\sqrt{s_{NN}} = 17\text{GeV}\))
First $J/\psi$ polarization measurement in PbPb collisions

- All polarization parameters are consistent with zero
- Result compatible with a first measurement at SPS energies (NA60, InIn@\(\sqrt{s_{NN}} = 17\text{GeV}\))
- Weak or no polarization in PbPb, as already in pp collisions
- Theory guidance needed!
Conclusions

In all collisions systems results are reaching a high-precision level and new observables are becoming accessible.

- **pp**: several aspects of quarkonium production are now extensively studied over a very broad kinematic range.

- **pA**: ground states production can be explained via “standard” CNM effects, while final state effects are needed for the excited states.

- **AA**: quarkonium $R_{AA}$ and elliptic flow measurements are interpreted in terms of suppression and recombination.

These results, spanning over several orders of magnitude in $\sqrt{s}$, will improve even further the path towards a consistent picture of all quarkonium states.

**Thanks!**
Backup Slides
Quarkonium sequential melting

<table>
<thead>
<tr>
<th>state</th>
<th>(J/\psi)</th>
<th>(\chi_c)</th>
<th>(\psi(2S))</th>
<th>(\Upsilon(1S))</th>
<th>(\Upsilon(2S))</th>
<th>(\Upsilon(3S))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (GeV)</td>
<td>3.10</td>
<td>3.51</td>
<td>3.69</td>
<td>9.46</td>
<td>10.0</td>
<td>10.36</td>
</tr>
<tr>
<td>(\Delta E) (GeV)</td>
<td>0.64</td>
<td>0.22</td>
<td>0.05</td>
<td>1.10</td>
<td>0.54</td>
<td>0.20</td>
</tr>
<tr>
<td>(r_o) (fm)</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
<td>0.28</td>
<td>0.56</td>
<td>0.78</td>
</tr>
</tbody>
</table>

(Digal, Petreci, Satz PRD 64(2001) 0940150)

Low \(p_T\) \(J/\psi\)  
Low \(p_T\) \(\Upsilon(1S)\)  

PHENIX, Phys.Rev C91, 024913

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Quarkonium production
Quarkonium polarization

Polarization parameters are evaluated from the angular distribution of decay muons in the quarkonium rest frame:

\[ W(\cos\theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \left( 1 + \lambda_\rho \cos^2 \theta + \lambda_\theta \sin^2 \theta \cos 2\phi + \lambda_\theta \sin 2\theta \cos \phi \right) \]

no significant J/ψ polarization from RHIC to LHC energies, up to \( p_T = 70 \text{ GeV/c} \) (CMS, PLB727(2013)381)

still some tension, between data and theory models, in the description of all polarization parameters

→ agreement improves with CGC+NRQCD calculation
Further constraints to the models may also come from comparison of different systems.

**RHIC:** many different AA collisions investigated

- smooth suppression pattern from pA to AA
- $R_{AA} < 1$ already in pA → CNM effects

precise pA measurements needed to quantitatively interpret AA results.
Charmonium in AA

Rise at very low $p_T$ at LHC energies
$\rightarrow$ suppression + regeneration mechanisms at play at $p_T < 2\text{GeV}/c$
Flat RAA up to high $p_T$ values for RHIC

New data

Old data
Charmonium in AA

**Transport models:** based on thermal rate eq. with continuous J/\( \psi \) dissociation and regeneration in QGP and hadronic phase


**Statistical hadronization:** J/\( \psi \) produced at chemical freeze-out according to their statistical weight

A. Andronic et al., NPA 904-905 (2013) 535

**Comover model:** J/\( \psi \) dissociated via interactions with partons - hadrons + regeneration contribution


All models fairly describe the data

but large uncertainties associated to charm cross section and shadowing (data precision better than the theory one)
Very low $p_T$ J/$\psi$

Large enhancement observed at low $p_T$ (<0.2 GeV/c) in the J/$\psi$ $R_{AA}$, in both Au-Au and U-U peripheral collisions

- effect similar to the one observed by ALICE for $p_T$<0.3 GeV/c (PRL116 (2016) 222301)
- cannot be described by hadronic production (color screening, regeneration, CNM effects)
- excess possibly due to coherent photon-nucleus interactions ($b<2R$)

STAR, arXiv:1904.11658
Multi-differential $J/\psi \ R_{AA}$

$R_{AA}$ vs $p_T$ for different centrality bins (and vice-versa) at $\sqrt{s_{NN}}=5.02$ TeV

Striking features observed in ALICE results
- no $R_{AA}$ centrality dependence in $0.3<p_T<2$ GeV/c
- $\sim 70\%$ suppression for central events at $p_T\sim 10$ GeV/c (as for CMS and ATLAS)

Zhao et al., NPA 859 (2011) 114
Further constraints to the models may also come from comparison of different systems.

**LHC**: few hours XeXe run in 2017

- Similar $R_{AA}$ in Xe-Xe and Pb-Pb ($A_{Xe} = 129$, $A_{Pb} = 208$)

- In TAMU transport model, for a given $N_{part}$
  - central collisions: the higher $N_{coll}$ and $\sqrt{s_{NN}}$ lead to a slightly larger regeneration in XeXe
  - peripheral/semi-central collisions: the larger nuclear overlap in XeXe induces a stronger suppression

Unfortunately, not all systems at RHIC and LHC have yet enough precision to allow detailed comparisons.
\(\psi(2S)\) in AA

\(\psi(2s)\) is a loosely bound state (binding energy: \(\psi(2s) \sim 60\) MeV, \(J/\psi \sim 640\) MeV)

High \(p_T\)

\(\psi(2S)\) suppression stronger than the \(J/\psi\) at high \(p_T\), as expected in a sequential suppression scenario

\(\psi(2S)\) is a loosely bound state (binding energy: \(\psi(2s) \sim 60\) MeV, \(J/\psi \sim 640\) MeV)

\(\psi(2S)\) suppression stronger than the \(J/\psi\) at high \(p_T\), as expected in a sequential suppression scenario
The CMS collaboration has investigated the nuclear modification factor $R_{AA}$ for $\psi(2S)$ production in PbPb collisions at the LHC. The data was collected at the CMS experiment at a center-of-mass energy of 5.02 TeV. The analysis was performed in the rapidity range $|y| < 1.6$ and for $6.5 < p_T < 30$ GeV/c.

High-$p_T$ region:
- $R_{AA}$ is shown for different $N_{\text{part}}$ values, indicating a suppression of $\psi(2S)$ production relative to the pp baseline.
- The suppression is stronger for $\psi(2S)$ compared to $J/\psi$ over all centralities.

Low-$p_T$ region:
- Similar trends are observed for low-$p_T$ values, with stronger suppression for $\psi(2S)$.

The CMS collaboration's study provides insights into the medium modification of heavy quark states in nucleus-nucleus collisions.
J/ψ in pA collisions at RHIC

J/ψ production in small systems now studied, also multi-differentially, in p-Al, p-Au, d-Au, ³He-Au

- limited CNM effects in p-Al data
- similar $R_{pA}$ increase vs $p_T$ in p-Au, d-Au, ³He-Au
$\rho_T$ dependence of $J/\psi$ $R_{pA}$

- Slightly different $y$ coverage in ALICE and LHCb, but rather similar $p_T$ dependences.
- Shadowing and energy loss models describe $R_{pA}$ vs $p_T$.
Can the suppression in AA be due to CNM effects?

assume $R_{AA} = R_{pA} \times R_{Ap}$ (as for shadowing dominance)

comparison of pA and AA results indicates that CNM effects cannot account for the observed $R_{AA}$ at high $p_T$
Excited charmonium states

ψ(2S) suppression is stronger than the J/ψ one, in particular at backward-\( y \) and at low \( p_T \), both at RHIC and LHC.

At LHC and RHIC energies

- formation time > crossing time

same effects expected for J/ψ and ψ(2S)
Excited charmonium states

- soft color exchanges between hadronizing $c\bar{c}$ and comoving partons (Ma, Venugopalan)
- “classical” comover model, with break-up $\sigma$ tuned on low energy data (Ferreiro)
- regeneration and dissociation in the QGP and hadronic phase (Rapp, Zhuang)
J/$\psi$ and $\psi(2S)$ comparison in pA

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Excited bottomonium states

Also the excited $\gamma$ states show a stronger suppression than $\gamma(1S)$ in pPb wrt pp

Final state effects might be needed to explain the observations, as for charmonium

Strong suppression for $\gamma(3S)$ wrt $\gamma(1S)$ at backward-$\gamma$, consistent with comovers model
Three states characterized by very different binding energies:

- $\Upsilon(1S)$: $E_b \approx 1100$ MeV
- $\Upsilon(2S)$: $E_b \approx 500$ MeV
- $\Upsilon(3S)$: $E_b \approx 200$ MeV

Sensitive in very different ways to the medium

With respect to charmonium:

- Limited recombination effects → interesting for sequential suppression studies
- More robust theoretical calculations, due to higher $b$ quark mass
- No $B$ hadron feed-down → simpler interpretation?

Some drawbacks

- Lower production cross sections
- Non negligible feed-down contributions from higher states

H. Wöhri, QWG2014

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Some tension in the $R_{AA}$ evolution vs $y$ with energy, but still large uncertainties

Suppression increases with $y$ at $\sqrt{s_{NN}} = 2.76\text{ TeV}$

Suppression is constant at $\sqrt{s_{NN}} = 5.02\text{ TeV}$

CMS-PAS-HIN16-023
CMS arXiv:1611.01510

E. Scomparin, QM17

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Bottomonium at RHIC

• Similar $\Upsilon(1S)$ suppression, within uncertainties, at RHIC and LHC
• Excited states suppression is stronger at LHC

$\sqrt{s}$-dependence of feed down and CNM effects need to be precisely quantified

Models describing LHC results also describe RHIC ones

$T_{(RHIC)} \sim 440$ MeV
$T_{(LHC)} \sim 630$ MeV

(M. Strickland, arXiv:1807.07452)

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Bottomonium in AA

comovers

anisotropic hydro

transport

All models agree with data within uncertainties

• regeneration now included in most of the models, but contribution is small

• comparison to models might help in determining the initial QGP $T$

$\sqrt{s_{NN}} = 5.02\text{TeV} \rightarrow T \approx 630\text{ MeV}$ (Krouppa-Strickland) $T \approx 550-800\text{ MeV}$ (Du, He, Rapp)

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