Measurements of quarkonium production at the LHC

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2024 RHIC/AGS Annual Users' Meeting
12. June. 2024 (Wed.)
Quarkonium production in heavy-ion collisions

- Initial idea: quarkonium production suppressed via colour screening in QGP
- Sequential melting: differences in the quarkonium binding energies lead to a sequential melting with increasing temperature

Adapted from
Quarkonium production in heavy-ion collisions

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- With larger $c\bar{c}$ cross section at the LHC energies, (re)generation of charmonium and charmed hadron production take place at the phase boundary or in QGP

Adapted from

Matsui and Satz, PLB 178 (1986) 416
Digal, Petrecki and Satz PRD 64 (2001) 094015
Braun-Muzinger, J. Stachel, PLB 490(2000) 196
R. L. Thews et al. PRC 63 (2001) 054905
Quarkonium production in heavy-ion collisions

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- With larger $c\bar{c}$ cross section at the LHC energies, (re)generation of charmonium and charmed hadron production take place at the phase boundary or in QGP

- Bottomonium @ LHC spends a longer time in a hotter medium, yet no significant regeneration ➔ genuine non-equilibrium probe of the full time evolution of QGP
Quarkonium measurements at the LHC

- S-wave quarkonium decays to dilepton pair:
  - $J/\psi \rightarrow ee$ ($5.971 \pm 0.032\%$), $J/\psi \rightarrow \mu \mu$ ($5.961 \pm 0.032\%$)
  - $Y(1S) \rightarrow \mu \mu$ ($2.48 \pm 0.05\%$)

- Four experiments provide complementary measurements different kinematic coverages

*For $J/\psi$ in Pb-Pb collisions (Run 2)
## Quarkonium measurements at the LHC

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- Four experiments provide complementary measurements different kinematic coverages

- **Caveat:** significant, $p_T$ dependent, feed-down contributions
  - From excited states
  - From beauty hadron ($H_b$) for charmonium; separation relying on long lifetime of $H_b$

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Adapted from J.P. Lansberg *Physics Reports* 889 (2020) 1
Nuclear modification factor ($R_{AA}$) of $J/\psi$ at the LHC

- Complementary measurements from different experiments, covering wide $p_T$ range
- Separate measurements of prompt and non-prompt $J/\psi$ originate from $h_B$
**J/ψ R_{AA}: interplay between regeneration and suppression**

**ALICE, PLB 849 (2024) 138451**

**ALICE, JHEP 02 (2024) 066**

**CMS, EPJC 78 (2018) 509**


- **Stronger** $R_{AA}$ increase towards lower $p_T$ in midrapidity, exhibiting comparable suppression at high $p_T$

- **Stronger** $R_{AA}$ increase towards lower $p_T$ in central events, exhibiting larger suppression at high $p_T$

⇒ Theoretical predictions support (re)generated J/ψ concentrated at low $p_T$ at midrapidity with larger cc cross section
**J/\psi** \( R_{AA} \) in different system energies

- **Strong rise of the J/\psi RAA from RHIC to LHC energies:** interplay between regeneration and suppression
- **Both SHM and Transport model simultaneously describe RHIC/LHC data**


\[
\sqrt{s_{NN}} = 2.76 \text{ TeV} \ (|y| < 0.8, \pm 13\% \text{ systematic uncertainty})
\]

\[
\sqrt{s_{NN}} = 0.2 \text{ TeV} \ (|y| < 0.35, \pm 12\% \text{ systematic uncertainty})
\]

\[
\sqrt{s_{NN}} = 0.2 \text{ TeV} \ (|y| < 1.0, \pm 14\% \text{ systematic uncertainty})
\]

\[d\sigma_{\gamma\gamma}/dy = 0.404 \pm 0.077 \text{ mb}\]

Lines: statistical hadronization


- This analysis: Au+Au, 14.6, 19.6, 27 GeV
- Au+Au, 54.4 GeV
- Au+Au, 39, 62.4, 200 GeV
- Pb+Pb, 17.3, 2760, 5020 GeV

\[J/\psi \ R_{AA} \]

\[d\sigma_{\gamma\gamma}/dy = 0.344 \pm 0.055 \text{ mb}\]

\[dN_{ch}/dy\big|_{y=0}\]


Y. Wang for STAR, QM2023 proceedings
Smaller theoretical uncertainties in the observable:
- initial state effects, such as shadowing, largely cancelled
- less dependent on the charm quark cross section

Hint of larger ratio over centrality and less pronounced centrality dependence w.r.t. NA50

TAMU reproduces the cross section ratios over centrality; while SHM underestimates
The suppression for $\psi(2S)$ is larger than for $J/\psi$ in measured $p_T$ range.

Increasing trend at low $p_T$ also in $\psi(2S) \rightarrow$ hint of $\psi(2S)$ regeneration.

More differential and improved precision measurements required → Run 3 + Run 4.
Bottomonium production in Pb-Pb collisions

Different sensitivity to the medium:
\[ Y(1S): \sim 1100 \text{ MeV} \quad Y(2S): \sim 500 \text{ MeV} \quad Y(3S): \sim 200 \text{ MeV} \]

Strong suppression vs centrality with sequential melting pattern:
\[ R_{AA}(Y(1S)) > R_{AA}(Y(2S)) > R_{AA}(Y(3S)) \]

Is bottomonium genuine thermometer of QGP?
- Feed-down contribution
(i.e. P-wave states \( \rightarrow \) excited \( \Upsilon \) not measured)
- Regeneration contribution
- Cold nuclear matter effects?
**Bottomonium production in Pb-Pb collisions**

Relative yield ($R_{AA}$) of excited state w.r.t. ground state: model discriminator

- Cancellation of sources of uncertainty both in measurement and theoretical predictions
- Different slopes between the models - in tension with Comovers and SHM
Quarkonium production in p-Pb collisions at the LHC

- A baseline for quark-gluon plasma study in HI collisions
- Probes the cold (or?) nuclear matter effects i.e.
  - nuclear modification of parton distribution functions
  - saturation in the colour Glass Condensate (CGC) approach
  - multiple scattering and energy loss
  - breakup by comovers …

P. Duwenstätter et al., PRD 105 (2022) 114043
nPDFs@NLO: improved precision using LHC measurements

P. Duwenstäter et al., PRD 105 (2022) 114043

+ Vector boson
+ Vector boson + inclusive hadron
+ inclusive quarkonium and open heavy-flavor production

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**J/ψ $R_{pA}$ in p-Pb collisions**

- Influence of rapidity dependent CNM effects; compatible with models including nPDF effects
- Mild suppression concentrated at low in $p_T$ midrapidity

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**ALICE, JHEP 07 (2023) 137**

![Graphs showing $R_{pPb}$ as a function of $y_{cms}$ and $p_T$](image)

- Influençe of rapidity dependent CNM effects; compatible with models including nPDF effects
- Mild suppression concentrated at low in $p_T$ midrapidity
Excited charmonium states in p-Pb collisions

- Stronger suppression of $\psi(2S)$ in backward-$y$ both at RHIC/LHC

- Initial-state effects or coherent energy loss; largely independent on the specific charmonium resonance $\rightarrow$ final-state effects? Comover model agrees with the measurement within uncertainty
Sequential suppression observed in p-Pb collisions with improved precision for Y(1S), Y(2S) and Y(3S) → yet much less than in Pb-Pb collisions

Suppression trend reproduced by nPDF + comover breakup Model
Sequential suppression observed in p-Pb collisions with improved precision for Y(1S), Y(2S) and Y(3S) → yet much less than in Pb-Pb collisions

Suppression trend reproduced by nPDF + comover breakup Model

Hot-medium effects describe Y suppression in pPb collisions as well
What kind of system is formed in p-Pb collisions?

- Systematic studies of quarkonium production in p-Pb collisions in backward-y as a function of binding energy

\[ R(\chi_c / J/\psi) \sim 1 \]

If there’s a collective system formed in p-Pb collisions, the free energy (or temperature) of the system to be no larger than 180 MeV

- Caveat: $\chi_c / J/\psi$ for $p_T > 2 \text{ GeV/c}$

- $R(Y(3S) / Y(1S)) < R(\chi_c / J/\psi) \sim 1$ despite of similar binding energies of $\chi_c$ and Y(3S)

- Impact of feed-down?
- Mass-dependent effects?
- P vs S-wave?
Quarkonium elliptic flow

- Good agreement in CMS and ALICE in various systems; without strong rapidity dependence found in current precision

- $J/\psi$: PbPb $v_2 \geq pPb \ v_2 > pp \ v_2 \approx 0$

- $Y(1S)$: PbPb $v_2 \approx pPb \ v_2 \approx 0$
Quarkonium elliptic flow

- **PbPb**: Regeneration process in transport model with thermalized $c$ and $\bar{c}$ quark spectra → $c$-quark phase space distributions from relativistic Langevin simulations (off-equilibrium spectra)

- **Non-zero $J/\psi$ $v_2$** in high multiplicity $p$-Pb collisions, underpredicted by theory including final-state collectivity at intermediate $p_T$
**Y(1S) elliptic flow**

CMS Collaboration, PLB 819 (2021) 136385

- No evidence for finite Y(1S) $v_2$ over measured $p_T$ range as in previous measurement
- Consistent with the different model predictions; but tension at high $p_T$
- $Y$ mesons much slower than other species due to their heavy mass
  - Low-$p_T$: $v_Y^Y < v_{QGP}^{flow}$ → Cannot escape QGP
  - Intermediate $p_T$: $v_Y^Y \simeq v_{QGP}^{flow}$ → Long effective travel distance (depending on axis direction)
  - High-$p_T$: $v_Y^Y > v_{QGP}^{flow}$ → Experience initial geometry from fast QGP escape
- Requires better precision measurement at high $p_T$

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Hong, Lee, PLB 801 (2020) 135147
Du, Rapp, PRC 96 (2017) 054901
Reygers et al., PRC 101 (2020) 064905
Yao et al., JHEP01 (2021) 046
Bhaduri et al., PRC 100 (2019) 051901
Reygers et al., x10^{-1} (10-20, 40-50, 60-70%)

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J. Park, Private communication
Measurements in pp collisions

- Provide reference for p-Pb and Pb-Pb collisions
- Understand production mechanism; both perturbative and non-perturbative QCD processes involved
- Quarkonium production associated with event properties: interplay between hard and soft particle, possible collectivity

ALICE Collaboration, JHEP 10 (2019) 084
ALICE Collaboration, EPJC 81 (2021) 1121

- complementary measurements different kinematic coverages with good agreements
- Small experimental uncertainties compared to theoretical uncertainties
Constraining models with various observables

V. Cheung and R. Vogt, PRD 104 (2021) 9, 094026

ALICE, EPJC 78 (2018) 562

LHCb, JHEP 05 (2024) 243

LHCb, PRL 118 (2017), 192001

Bain et al., PRL 119 (2017), 032002
Charmonium production vs. event activity

- ALICE $\psi(2S)/J/\psi$ (fwd-y) vs. mid-y mult. compatible with
  - unity presented in PYTHIA
  - Linear decrease trend in comover model

- LHCb prompt $\psi(2S)/J/\psi$ (fwd-y) vs. mult. favored in linear decrease trend in comover model; slope changes based on $\Delta \eta$ difference between quakonium and multiplicity window

- Non-prompt $\psi(2S)/J/\psi$ (fwd-y) vs. mult. consistent with unity and no $\Delta \eta$ dependence seen
Bottomonium production vs. event activity

- $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ decreases with multiplicity in pp as well as in p-Pb collisions.
- Decreasing trend with multiplicity seen for all azimuthal angles at high $p_T$.

$\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ decreases with multiplicity in pp as well as in p-Pb collisions.
Summary and outlook

- Higher precision, more differential measurements achieved in all collision systems and **new observables become accessible** for quarkonium sector

- **Pb-Pb collisions:**
  - interplay of suppression and regeneration
  - strong hints for charm quark thermalization in QGP, yet open questions left

- **p-Pb collisions:** more than initial state cold nuclear matter effects?

- **pp collisions:** deeper understanding of quarkonium production mechanism and effects of underlying event
Topics not covered today: Double Parton Interaction

Associated quarkonium production $\rightarrow$ Direct probe for MPI

LHCb, JHEP 2308 (2023) 093
Topics not covered today: Search for exotica

CMS, PRL 132 (2024) 111901
Topics not covered today: Role of quarkonium in UPCs

ALICE, PRL 132 (2024) 162302

ALICE, JHEP 10 (2023) 119
Summary and outlook

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- Not covered today: **LHC Run 3 program started and smoothly ongoing!!**
  → much larger data sample expected with upgrade detectors

**STAY TUNED!!**