Quarkonia production and elliptic flow in small systems measured with ALICE

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on behalf of the ALICE Collaboration

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Outline

- Quarkonium production
- Multiplicity-dependent quarkonium production
- Elliptic flow
- $J/\psi$ pair production
Why quarkonia in small systems?

**Constrain theoretical models:**

- **Color Evaporation Model [1]:**
  - pQCD Statistical approach
  - Describes well quarkonia production
  - No distinction between color singlet or octet mechanisms

- **NRQCD [2]:**
  - NRQCD formalism
  - Predicts well cross sections

- **Beauty production via non-prompt charmonia:**

- **Fixed Order Next-to-Leading-Logarithm [3]:**
  - pQCD for heavy quark production
  - Used for non-prompt J/ψ (ψ(2S)) production, predicts well data

**Shed light on Multiple Parton Interactions (MPI):**

- Multiplicity dependent measurements
  - → Quarkonia correlations with charged-particle multiplicity / flow

- Heavy quarks created in subsequent hard-scattering processes, in early stage of collision

**Investigate collectivity in small systems**

- Study of J/ψ elliptic flow at high collision energy and multiplicity

**Reference for measurements in p—Pb and Pb—Pb collisions**

[3]: JHEP 9805:007, 1998
A Large Ion Collider Experiment

Time Projection Chamber:
Charged particle tracking
Particle identification

Inner Tracking System:
Particle tracking
Vertex reconstruction

V0:
Trigger detector
Event characterization
Background rejection

Inclusive quarkonia measurements down to $p_T = 0$ GeV/c:
$J/\psi \rightarrow e^+e^-$
(prompt/non-prompt separation)
Midrapidity: $|y_{ee}| < 0.9$

$J/\psi, \psi(2S), \Upsilon(nS) \rightarrow \mu^+\mu^-$
(inclusive quarkonium states)
Forward rapidity: $2.5 < y_{\mu\mu} < 4$

Muon Spectrometer:
Muon tracking
Muon trigger
**J/ψ production measurement in pp collisions:**

Muonic decay channel: $J/ψ \rightarrow μ^+μ^−$

Forward rapidity: $2.5 < y < 4$

Down to $p_T = 0$ GeV/c

$\sqrt{s} = 5.02, 7, 8, \text{ and } 13$ TeV

**Cross section measurements vs $p_T$:**

Agreement between data and NRQCD + FONLL model

Cross section increases with increasing collision energy
**J/ψ production measurement in pp collisions:**
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**Ratio vs $p_T$:**
- Agreement for 8-to-13 TeV and 5-to-13 TeV ratios
- 7-to-13 TeV ratio slightly overestimated by model

Hardening of $p_T$ spectra at 13 TeV compared to lower energies:
- Predicted increase of prompt J/ψ mean $p_T$ with energy
- Increase of non-prompt J/ψ contribution at high $p_T$ (FONLL predictions)
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**J/ψ production at midrapidity**

**J/ψ production measurement in pp collisions:**

- Electron decay channel: $J/\psi \rightarrow e^+e^-$
- Midrapidity: $|y| < 0.9$
- Down to $p_T = 1 \text{ GeV/c}$ for $\sqrt{s} = 13 \text{ TeV}$
- Down to $p_T = 2 \text{ GeV/c}$ for $\sqrt{s} = 5.02 \text{ TeV}$

**Cross section measurements vs $p_T$:**

- **Prompt J/ψ:**
  - ICEM + NRQCD based models: in agreement with data
  - NRQCD Lipatov calculations: slightly overestimate data at low $p_T$

- **Non-prompt J/ψ:**
  - In agreement with FONLL model

**Fraction of the non-prompt J/ψ:**

$$f_{\text{visible},\sqrt{s}=13 \text{ TeV}}(p_T > 1 \text{ GeV/c}, |y| < 0.9) = 0.185 \pm 0.015(\text{stat.}) \pm 0.014(\text{syst.})$$

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- Non-prompt J/ψ:
  - In agreement with FONLL model

Fraction of the non-prompt J/ψ:
\[ f_B^{\text{visible}, \sqrt{s}=5.02 \text{ TeV}} (p_T > 2 \text{ GeV}/c, |y| < 0.9) = 0.157 \pm 0.023(\text{stat.}) \pm 0.016(\text{syst.}) \]

Comparison with CMS and ATLAS data, consistency is observed in the common p_T region
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Indication of decrease of non-prompt fraction at lower collision energy

Comparison with CMS and ATLAS data, consistency is observed in the common $p_T$ region
ψ(2S) production measurement in pp collisions:

- Muonic decay channel: $\psi(2S) \rightarrow \mu^+\mu^-$
- Forward rapidity: $2.5 < y < 4$
- Down to $p_T = 0$ GeV/c
- $\sqrt{s} = 5.02, 7, 8,$ and $13$ TeV

Cross section measurements vs $p_T$:

- Agreement between data and NRQCD + FONLL model
- Increase of $\psi(2S)$ cross section with increasing collision energy
Excited charmonia: $\psi(2S)$ production

- **$\psi(2S)$ production measurement in pp collisions:**
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- **Cross section measurements vs $p_T$:**
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- **Cross section ratio of $\psi(2S)$-to-J/$\psi$ vs $p_T$:**
  - Ratio increases with increasing $p_T$, no energy dependence
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$\psi(2S)$ production, as $J/\psi$, increases with collision energy - what about multiplicity-dependent production?
Multiplicity-dependent quarkonium production

Normalized yield

No Underlying-Event dependence

Normalized charged particle multiplicity
Scale with mean multiplicity (MPI)
Multiplicity-dependent quarkonium production

Interplay of complex effects
**J/ψ production measurement:**
- Electron decay channel: $J/ψ \rightarrow e^+e^-$
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- Forward rapidity: $2.5 < y < 4$
- With $\sqrt{s} = 5.02$ TeV, and 13 TeV

**Production measurement vs charged particle multiplicity:**
- **Midrapidity region:** stronger than linear increase of the yield with the multiplicity
- **Forward rapidity region:** trend compatible with linear dependence on multiplicity, independent of the center-of-mass energy
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**Comparison with models:**
CPP, CGC, and 3-Pomeron models in agreement with the inclusive midrapidity data

Faster-than-linear increase predicted by different models due to different mechanisms:
Color string reconnection, gluon saturation, coherent particle production, 3-gluon fusion in gluon ladders/Pomerons
Multiplicity-dependent quarkonium production

✓ J/ψ production measurement:
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What about the excited charmonium states?

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Relative $\psi(2S)$-to-$J/\psi$ production vs multiplicity

**ψ(2S) production measurement at forward $y$ as a function of charged particle multiplicity (mid-$y$) in pp:**

Linear correlation of $\psi(2S)$ production with charged particle multiplicity, self-normalized $\psi(2S)/J/\psi$ compatible with unity

**Conclusion:** Production at forward rapidity independent of the charmonium state + collision energy

$\psi(2S)$ yield: PYTHIA, with/without color reconnections, in agreement with data at low multiplicity, tension at high multiplicity

$\psi(2S)$-to-$J/\psi$ ratio: tension at low multiplicity between data and PYTHIA $\rightarrow$ different event activity bias to explain the discrepancy?
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Collectivity at high multiplicity in small system?
The elliptic flow coefficient for small system:
\[ v_2(p_T, y) = \langle \cos(2\Delta\phi) \rangle \]

**J/ψ elliptic flow measurement vs \( p_T \):**
- First results in pp down to 0 GeV/c
- No significant deviation of J/ψ \( v_2 \) from zero
  → No collective behavior observed in pp collisions at high multiplicity for the J/ψ

Comparison between pp, p–Pb, and Pb–Pb collisions: for the latter, presence of collective behavior, with a clear difference w.r.t pp data
\[ v_{2,J/ψ}^{pp} < v_{2,J/ψ}^{Pb} < v_{2,J/ψ}^{PbPb} \]

*NEW*

**ALICE Preliminary**

- Pb–Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV}, (30-50\%) \) (JHEP 10 (2020) 141)
  - 2.5 < \( y \) < 4.0
- p–Pb, \( \sqrt{s_{NN}} = 5.02, 8.16 \text{ TeV}, (0-20\%)-(40-100\%) \) (PLB 780 (2018) 7-20)
  - 1.5 < \( |y| \) < 5.0, 2.03 < \( y \) < 3.53
- pp, \( \sqrt{s_{NN}} = 13 \text{ TeV}, (0-5\%)-(40-100\%) \)
  - 1.5 < \( |y| \) < 5.0, 2.5 < \( y \) < 4.0

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**J/ψ pair production measurements at 13 TeV:**
Disentangle mechanisms for J/ψ production
Constraints on CS and COM models
Insights on double parton scattering
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**di-J/ψ production cross section:**
Consistency with LHCb cross section measurement observed

(!) Prompt J/ψ measured in LHCb, inclusive J/ψ in ALICE
(!) Slightly different rapidity ranges
**Conclusion**

- **Quarkonium production in pp collisions:**
  - Well described by models
  - $J/\psi$ and $\psi(2S)$ cross section increases with energy
  - $\psi(2S)$-to-$J/\psi$ ratio: increases with increasing $p_T$ + independent of energy

- **Measurements of multiplicity dependent charmonium production in pp collisions:**
  - Different behavior versus charged particle multiplicity for the $J/\psi$ produced at mid and forward rapidity
  - Same trend versus multiplicity for the $J/\psi$ and $\psi(2S)$ at forward rapidity

- **First elliptic flow measurements for $J/\psi$ in pp collisions at 13 TeV:**
  - No evidence for positive $J/\psi$ elliptic flow in high multiplicity events

- **First $J/\psi$ pair production measurements in pp collisions:**
  - First results of double $J/\psi$ cross section: in agreement with LHCb

**Perspective for Run 3:**

- Larger multiplicity can be achieved with increased statistics
- Better S/B for quarkonium measurements
- Separation of the prompt and non-prompt $J/\psi$ at forward rapidity thanks to the Muon Forward Tracker
- Improved spatial resolution at midrapidity thanks to the upgraded ITS
Thank you for your attention!