Quarkonium measurements at forward rapidity with ALICE at the LHC

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A Large Ion Collider Experiment

Silicon Pixel Detector
- vertexing
- multiplicity

V0 detectors
- luminosity
- min. bias trigger
- centrality
- event-plane

Zero Degree Calorimeter
- centrality in p-Pb
- background rejection

Measurement of quarkonia at forward rapidity via dimuon decay channel, down to $p_T = 0$

Muon spectrometer (-4 < $\eta$ < -2.5)
- trigger and tracking
Event activity dependence

Physics motivations:

- test production mechanisms
- study the role of multi-parton interactions in quarkonium production
- observe potential collective-like effects in small systems

Correlation of forward quarkonium production with event activity at mid-rapidity

Presence of Cold Nuclear Matter effects in p-Pb to be taken into account

forward quarkonium

event activity in |η| < 1

**In pp collisions at \( \sqrt{s} = 5.02 \) and 13 TeV:**

- **linear increase** with multiplicity
- independent of energy and quarkonium state
Relative production yield


In pp collisions at $\sqrt{s} = 5.02$ and 13 TeV:
- linear increase with multiplicity
- independent of energy and quarkonium state

In p-Pb collisions at $\sqrt{s_{_{NN}}} = 8.16$ TeV:
- continuous rising at backward rapidity
- increase of forward yields slows down for high multiplicity classes
Mean transverse momentum

Dependence of J/ψ $\langle p_T \rangle$ on charged-particle multiplicity at mid-rapidity.

- increase of $\langle p_T \rangle$ in pp collisions: stronger in low multiplicity than in the higher region
Mean transverse momentum

Dependence of J/ψ \( \langle p_T \rangle \) on charged-particle multiplicity at mid-rapidity.

- Increase of \( \langle p_T \rangle \) in pp collisions: stronger in low multiplicity than in the higher region.

**Relative \( \langle p_T \rangle \) in small systems:**

- Increase in low multiplicity region
- Saturation in p-Pb while a continuous rising is observed in pp
Quarkonium suppression

Originally proposed as a *smoking gun of the deconfinement* in heavy-ion collisions

- color screening in QGP ➔ suppression of quarkonium production [PLB 178 (1986) 416]
- different binding energies for quarkonia ➔ sequential melting [PRD 64 (2001) 094015]

Cold Nuclear Matter effects

- modification of the PDF
- parton energy loss
- interaction with comovers ➔ addressed in p-Pb collisions


- statistical production of quarkonia via (re)combination of *thermalized* quarks in QGP or at hadronization stage
- significant enhancement expected for charmonium, little to no enhancement for bottomonium at LHC
Charmonium $R_{ppb}$ at $\sqrt{s_{NN}} = 8.16$ TeV

- $J/\psi$ suppression trend can be explained by initial-state effect models only
- Stronger suppression for $\psi(2S)$, especially at backward rapidity
  - Final-state effects needed to reproduce the suppression
Bottomonium $R_{pPb}$ at $\sqrt{s_{NN}} = 8.16$ TeV

- $\Upsilon(1S)$ suppression compatible with LHCb results, stronger at forward rapidity
- *tension* of shadowing and energy loss models with data in the backward region
- $\Upsilon(2S)$ slightly more suppressed than $\Upsilon(1S)$, reproduced by shadowing + comovers
Inclusive $J/\psi$ $R_{AA}$

- **weaker suppression** with respect to RHIC
- interpreted as a large contribution of **regeneration** at LHC energies

![Graph showing Inclusive $J/\psi$ $R_{AA}$](image)

**PLB 766 (2017) 212**
weaker suppression with respect to RHIC interpreted as a large contribution of regeneration at LHC energies

similar magnitude in Xe-Xe and Pb-Pb collisions

well described by Transport Model [NPA 943 (2015) 147] within uncertainties

triple-differential ($y, p_T, \text{centrality}$) $R_{AA}$ possible with new pp reference
Y(1S) suppression increases with centrality, described by model predictions

Y(2S) more suppressed ⇒ Y(2S)/Y(1S) $R_{AA}$ ratio = 0.28 ± 0.12 (stat) ± 0.06 (syst)

No significant dependence on $p_T$ and rapidity

More precise measurements to come with full Run 2 data
Azimuthal anisotropy

Motivation: study transport properties of the medium in non-central collisions via momentum distribution of the produced final-state particles.

- evaluate the harmonic coefficients of the Fourier expansion of the azimuthal particle distribution:
  - $v_2 = \text{"elliptic flow"}$
  - $v_3 = \text{"triangular flow"}$

Taken from arXiv:1611.01533
Positive $v_2$ in Pb-Pb and p-Pb for $p_T > 3$ GeV/c, underestimated by model at higher $p_T$.

- First measurement of triangular flow for J/$\psi$ in Pb-Pb (2015 dataset).
- $3.7\sigma$ significance for a positive $v_3$.

**Figure:**
- Plot showing $v_2$ vs. $p_T$ for Pb-Pb collisions, with different pseudorapidities and $s_{NN}$ values.
- Model predictions compared to data points.

**References:**
- PLB 780 (2018) 7-20
- PRL 119 (2017) 242301
First measurement of $\Upsilon(1S)$ elliptic flow

- $v_2$ compatible with zero (a non-zero flow is measured for all other hadrons !)
- $2.6\sigma$ lower than $J/\psi$ $v_2$ in $2 < p_T < 15 \text{ GeV/c}$

arXiv:1907.03169
First measurement of $\Upsilon(1S)$ elliptic flow

- $v_2$ compatible with zero (a non-zero flow is measured for all other hadrons !)
- $2.6\sigma$ lower than $J/\psi$ $v_2$ in $2 < p_T < 15$ GeV/c
- $v_2$ compatible with the small values predicted by the available theoretical models including regeneration (TAMU) or not (KSU)
**J/ψ polarisation**

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

Polarisation parameters evaluated from the angular distribution of decay muons in the quarkonium rest frame.

**NEW !**

from EPJC (2010) 69: 657-673

First measurement in Pb-Pb collisions (2015 only)

› compatible with zero
J/ψ polarisation

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Polarisation parameters evaluated from the angular distribution of decay muons in the quarkonium rest frame.

First measurement in Pb-Pb collisions (2015 only)

- compatible with zero and with pp results in both reference frames
J/ψ polarisation

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from EPJC (2010) 69: 657-673

Polarisation parameters evaluated from the angular distribution of decay muons in the quarkonium rest frame.

First measurement in Pb-Pb collisions (2015 only)

- compatible with zero and with pp results in both reference frames
- consistent with the first measurement at SPS
- study centrality dependence with 2018 dataset!
Summary

ALICE measurements of quarkonia at forward rapidity are of great interest to study heavy-ion physics at LHC

- multiplicity dependence in *small systems*
  - *increase* of production yield and $\langle p_T \rangle$ with charged-particle multiplicity

- suppression of quarkonium production
  - final-state effects needed to explain excited-state suppression in p-Pb
  - *regeneration of* $J/\psi$ and *sequential suppression of bottomonia* in AA

- anisotropy in azimuthal particle distribution
  - transport model does not describe positive $J/\psi$ $v_2$ at high $p_T$ in p-Pb and Pb-Pb
  - positive $J/\psi$ $v_3$ (3.7$\sigma$) and $\Upsilon(1S)$ $v_2$ compatible with zero

- first measurement of $J/\psi$ polarisation parameters in Pb-Pb

... and much more to come with full Run 2 data analysis!
Backup
Mean $p_T$ of inclusive J/$\psi$ in p-Pb

ALICE Preliminary
Inclusive J/$\psi \rightarrow \mu^+\mu^-$, p-Pb $\sqrt{s_{\text{NN}}} = 8.16$ TeV
Mult. classes: $|\eta|<1$

$\langle p_T \rangle$ (GeV/c)

$\langle p_T \rangle / \langle p_T \rangle_{\text{MB}}$

$\frac{dN_{\text{ch}}}{d\eta} \bigg|_{\text{NSD}}$ $\frac{\langle dN_{\text{ch}} / d\eta \rangle}{\langle dN_{\text{ch}} / d\eta \rangle_{|\eta|<1}}$

p-going ($2.03 < y_{\text{cms}} < 3.53$)
Pb-going ($-4.46 < y_{\text{cms}} < -2.96$)

$\pm 4.5\%$ global uncertainty

$\pm 3.4\%$ global uncertainty in p-going dir.
$\pm 2.3\%$ global uncertainty in Pb-going dir.

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Conventions for the definition of the polarisation $z$-axis:

- Collins-Soper (CS) = bisector of the angle between one beam and the opposite of the other beam
- Helicity (HX) = flight direction of the quarkonium in the centre-of-mass of the beams
J/ψ polarisation in proton-proton
Charmonium $Q_{pPb}$

ALICE Preliminary, p-Pb $\sqrt{s_{NN}} = 8.16$ TeV, Inclusive $J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$

$-4.46 < y_{\text{cms}} < -2.96, p_T < 20$ GeV/c

Transport Model (Du, Rapp, NPA 943(2015) 147)

Comovers + EPS09LO (Ferreiro, PLB 749 (2015) 98)

Backward rapidity

Forward rapidity
Transport models are not able to describe the data trend at high $p_T$. 

**Inclusive J/ψ $v_2$ in Pb-Pb**

ALICE 20 - 40% Pb-Pb, $|s_{NN}| = 5.02$ TeV

- Inclusive $J/ψ \rightarrow \mu^+\mu^-$, $2.5 < y < 4$, $v_2\{EP, \Delta\eta = 1.1\}$, global syst : 1%