Recent results on quarkonia in AA collisions from ALICE at the LHC

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On behalf of the ALICE collaboration

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**What?** Quark-gluon plasma: state of nuclear matter for which degrees of freedom are carried by quarks and gluons, as opposed to hadrons (confinement)

**Why?** To study the nuclear matter properties at high pressure and temperature

**How?** Lattice QCD computations predict a phase transition at $T_c = 155 \pm 9$ MeV


QGP should be created in heavy-ion collisions provided that energy density is large enough ($> 1$ GeV/fm$^3 \sim 6 \times$ nuclear density)

**Collision systems:**
- **pp** used as reference (no QGP expected)
- **pA** Cold nuclear effects (nuclear medium)
- **A–A** Hot nuclear effects (QGP) + Cold nuclear effects
Time evolution of heavy-ion collision

Probe? Quarkonia: meson bound states formed of a pair of heavy quark + anti-quark

Why? Heavy-quark pairs are produced in the initial hard-partonic collisions (pre-equilibrium) → Quarkonia are sensitive to the full evolution of the system and interact with the QGP

How? By measuring the quarkonium production in pp, pA and A–A collision systems

Observables: Nuclear modification factor ($R_{AA}$), elliptic flow ($v_2$), etc

Quarkonium states are expected to provide information on deconfinement and the QGP properties
1. Quarkonium measurements with ALICE

2. pp collisions: reference production

3. pA collisions: cold nuclear matter effects

4. A–A collisions: QGP study
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ALICE apparatus

Quarkonia measured down to zero $p_T$ via the reconstruction of their leptonic decay products:

- **Mid-rapidity**: $|y| < 0.9$
  - dielectron decay channel
  - ITS, TPC, TOF, TRD: vertexing, tracking, PID, trigger

- **Forward-rapidity**: $2.5 < y < 4$
  - dimuon decay channel
  - Muon spectrometer: tracking, trigger

V0, T0 and ZDC provide: MB trigger, centrality, event plane, luminosity

### Run-1 (2009-2013)

- **Pb–Pb**: $\sqrt{s_{NN}} = 2.76$ TeV
- **p–Pb**: $\sqrt{s_{NN}} = 5.02$ TeV
- **pp**: $\sqrt{s} = 0.9, 2.76, 7, 8$ TeV

### Run-2 (since 2015)

- **Pb–Pb**: $\sqrt{s_{NN}} = 5.02$ TeV
- **p–Pb**: $\sqrt{s_{NN}} = 5.02, 8.16$ TeV
- **pp**: $\sqrt{s} = 5, 13$ TeV
Quarkonium yields are extracted by fitting the dilepton invariant mass distribution or counting technique.

| $|y| < 0.9$ - dielectrons

| $2.5 < y < 4$ - dimuons

**Figure 1:**
- **Top left:** ALICE Performance
  - $p_{T} = 13$ TeV, 0-0.1% V0M
  - Data, MC signal + background
  - Background (exp)
  - $\chi^{2}/ndf = 1.3$
  - Bin counting window:
    - $2.92 < m_{ee} < 3.16$ GeV/$c^{2}$
    - $S/B = 2.75 \pm 0.14$

- **Top right:** ALICE pp $\sqrt{s} = 13$ TeV, $L_{int} = 3.2$ pb$^{-1} \pm 3.4$
  - $0<p_{T}<30$ GeV/$c$
  - $\chi^{2}/ndf = 2.17$
  - $N_{MC} = 339660 \pm 850$
  - $m_{ee} = 3099 \pm 0.2$ MeV/$c^{2}$
  - $\sigma_{ee} = 70 \pm 0.2$ MeV/$c^{2}$
  - $N_{V0M} = 8280 \pm 290$

- **Bottom left:** ALICE pp $\sqrt{s} = 8$ TeV, $L_{int} = 1.28$ pb$^{-1}$
  - $0<p_{T}<12$ GeV/$c$
  - $\chi^{2}/ndf = 1.1$
  - $N_{MC} = 460 \pm 40$
  - $m_{ee} = 9482 \pm 14$ MeV/$c^{2}$
  - $\sigma_{ee} = 132 \pm 14$ MeV/$c^{2}$
  - $N_{V0M} = 134 \pm 26$
  - $N_{V0M} = 46 \pm 23$
Outline

1. Quarkonium measurements with ALICE

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3. pA collisions: cold nuclear matter effects

4. A–A collisions: QGP study
**pp collisions: reference production (charm illustration)**

**pp collisions:** small energy density → no QGP expected → test bench for QCD

- Heavy quarks produce in hard-scattering process (pQCD applicable)
  - gluon fusion dominant at LHC energies, sensitive to gluon PDFs
- Non-perturbative evolution into color neutral bound states
  - ~ 90% open charm
  - ~ 10% charmonia

Models for the quarkonium production mechanisms:


**quarkonium cross sections measured in pp collisions as baseline to quantify the nuclear matter effects**

Basically, the ideal reference is the total charm cross section
(nuclear medium could modify the fraction of produced \( c\bar{c} \) pairs going into charmonium formation)

→ Run-3: ALICE will measure the open charm component down to zero \( p_T \)
- **J/ψ** production has been measured at all available LHC energies
- Spectra become harder with increasing energy → onset of the non-prompt J/ψ contribution
- Slope changes at high $p_T$ and $\sqrt{s} = 13$ TeV

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**Quarkonia production cross sections**


$\Upsilon$
Model comparisons

NRQCD: [PRL, 106 (2011) 042002]
NRQCD+CGC: [PRL, 113 (2014) 192301]
FONLL: [JHEP, 1210 (2012) 137]
Model comparisons

**NRQCD:** [PRL, 106 (2011) 042002]
**NRQCD+CGC:** [PRL, 113 (2014) 192301]
**FONLL:** [JHEP, 1210 (2012) 137]

Sum of the prompt (NRQCD) and the non-prompt (FONLL) contributions assuming fully uncorrelated uncertainties.

Charmonium cross sections well described by QCD-based models over the full $p_T$ range.
Inclusive $J/\psi$ polarization at forward rapidity

Polarization determined from angular distribution of muons in both Collins-Soper and Helicity frames:

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

No polarization of inclusive $J/\psi$ within uncertainties

Tension between models and experimental results

**NLO CSM:** [PRL, 108 (2012) 172002]
**NLO NRQCD:** [PRL, 108 (2012) 172002]
**NLO NRQCD2:** [PRL, 108 (2012) 242004]
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pA collisions: cold nuclear matter effects

Different mechanisms:

- **Saturation (CGC)** [Nucl. Phys. 1924 (2014)]
- **Energy loss (initial/final state, or coherent)** [PRL 109 (2012) 122301]
- **Comovers absorption** [PLB 749 (2015) 98]

Open question: is the energy density large enough yet for QGP formation?
J/ψ and ψ(2S) $R_{pPb}$

- J/ψ suppression at forward rapidity, $R_{pPb}$ compatible with unity at backward rapidity
- Models based on different shadowing implementations, CGC and energy loss fairly describe the J/ψ data
- Stronger ψ(2S) suppression than the J/ψ one, especially at backward rapidity
- Theoretical predictions based on shadowing and energy loss cannot describe the ψ(2S) data
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- Theoretical predictions based on shadowing and energy loss cannot describe the ψ(2S) data
- Comovers model including final-state effects reproduces the data also at backward rapidity

Final-state effects needed to explain the ψ(2S) behaviour (quarkonium formation time longer than crossing time)
- Similar γ(1S) suppression at forward and backward rapidity
- Models based on shadowing and/or energy loss reproduce the forward rapidity data but slightly overestimate the backward rapidity data.
ALICE Preliminary

Inclusive $\Upsilon(1S), \Upsilon(2S), p-Pb \sqrt{s_{NN}} = 8.16$ TeV, $p_T < 15$ GeV/c

- Similar $\Upsilon(1S)$ suppression at forward and backward rapidity
- Models based on shadowing and/or energy loss reproduce the forward rapidity data but slightly overestimate the backward rapidity data
- $\Upsilon(2S)$ suppression consistent with the $\Upsilon(1S)$ suppression with a hint for a stronger suppression of $\Upsilon(2S)$ (as observed by CMS and ATLAS at mid-$y$)
- Similar CNM effects for $\Upsilon$ at backward and forward rapidity
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**Pb–Pb collisions**: Quantify the hot nuclear matter effects from the QGP and extract its properties

Different mechanisms for quarkonia:

- Dissociation via an effective screening of the inter-quark force induced by the high density of color charges in the QGP
  - Different binding energy of quarkonium states $\rightarrow$ sequential suppression?
  - This could provide a measurement of the QGP temperature ...

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Quarkonia in AA collisions  
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- **Enhancement via the recombination of uncorrelated $Q$ and $\bar{Q}$ quarks present in the medium**
  - (Re)generation should decrease with increasing rapidity
  - (Re)generated quarkonia should be concentrated at low transverse momentum
Small suppression at higher energy for the most central collisions

- Smaller suppression at higher energy for the most central collisions
- Indication for smaller suppression at mid-rapidity with respect to forward rapidity
- In agreement with (re)generation scenario
- All the models including a (re)generation component reproduce the data for the most central collisions
- Large uncertainties mostly from $\sigma_{cc}$ and CNM effects
\( \frac{J/\psi}{R_{AA}} \) \text{ v.s. centrality}

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**J/ψ** \( R_{AA} \) v.s. centrality

![Graph showing J/ψ suppression in AA collisions](image)

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- Large uncertainties mostly from \( \sigma_{c\bar{c}} \) and CNM effects.

\[ R_{AA} = \frac{N_{\text{AA}}}{N_{\text{pp}}} \]

**ALICE, Pb–Pb** \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

Inclusive \( J/\psi \rightarrow \mu^+\mu^- \),

\[ 2.5 < y < 4, \ 0.3 < p_T < 8 \ \text{GeV/c} \]

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New collisional system at LHC: Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV ($L_{\text{int}} = 0.34 \mu b^{-1}$)

The $R_{AA}$ results of Xe–Xe and Pb–Pb agree within uncertainties

Similar $\sqrt{s_{NN}}$ and $\langle N_{\text{part}} \rangle$ lead to similar relative contributions of suppression/(re)generation
In clear contrast with the $p_T$ dependence measured at lower energy by PHENIX.
In clear contrast with the $p_T$ dependence measured at lower energy by PHENIX

- Transport model including (re)generation component reproduces well the data
In clear contrast with the $p_T$ dependence measured at lower energy by PHENIX.

Transport model including (re)generation component reproduces well the data.

Higher $R_{AA}$ at mid-rapidity than forward for the low-$p_T$ region.

In agreement with (re)generation scenario.
Strong $\Upsilon(1S)$ suppression in most central collisions (0–10%): $0.33 \pm 0.03{\text{(stat)}} \pm 0.03{\text{(syst)}}$

Stronger $\Upsilon(2S)$ suppression (integrated centrality): $0.10 \pm 0.04{\text{(stat)}} \pm 0.02{\text{(syst)}}$

$\Upsilon(2S)$ to $\Upsilon(1S) R_{AA}$ ratio is $0.28 \pm 0.12{\text{(stat)}} \pm 0.06{\text{(syst)}}$

**Sequential suppression?**
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Sequential suppression?

Transport and hydro-dynamical models fairly reproduce the data

Open question: is the direct $\Upsilon(1S)$ production suppressed?

→ Feed-down fraction and CNM effects not enough precisely known
$R_{AA}$ v.s. $p_T$ and $y$

No significant $p_T$ and rapidity dependence
的压力梯度在一个热化介质中，将初始的空间各向异性转化为动量空间的各向异性

- 各向异性由四元展开中粒子法线分布的第二阶系数 $v_2$ 表征

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Phi_R)) \right]$$
Positive open charm D-meson $v_2$

$\rightarrow$ Strong coupling of charm quark with the medium

Is the J/$\psi$ inherit any of the fireball collective flow via (re)generation?
J/ψ elliptic flow $v_2$

- Positive open charm D-meson $v_2$
  - Strong coupling of charm quark with the medium

Is the J/ψ inherit any of the fireball collective flow via (re)generation?

- Clear J/ψ $v_2$ signal ($\approx 6\sigma$) observed at forward rapidity
- Similar $v_2$ for open and hidden charm

- Low-$p_T$: data fairly well described by transport models
- High-$p_T$: $v_2$ underestimated by the model calculations based on path-length dependent suppression in QGP?

Further signs of charm thermalization and recombination
**J/ψ elliptic flow $v_2$**

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**Further signs of charm thermalization and recombination**
Back to p–Pb: J/ψ elliptic flow $v_2$

Regeneration negligible due to low production of charm quarks

Negligible path-length dependence regarding the small system size

- **Low-$p_T$:** $v_2$ compatible with zero
  → agree with no regeneration

- **High-$p_T$:** positive $v_2$
  → similar to the Pb–Pb measurement!!
  Not understood

Similar magnitude of $v_2$ in p–Pb and Pb–Pb could indicate a common mechanism
Low $p_T$ J/$\psi$ excess

- **Run-1:** An excess of J/$\psi$ has been observed at very low-$p_T$ in peripheral collisions at forward rapidity.

  - Interpreted as coherently photo-produced J/$\psi$
  - $\langle p_T \rangle \sim 60$ MeV/c

- **Run-2:** Measurement of this excess at mid-rapidity

A suppression of the coherent J/$\psi$ photo-production in hadronic collisions could be a direct probe of the color screening mechanism (not mimicked by regenerated J/$\psi$)
Corrected J/ψ yields, after subtraction of the hadronic contribution, \(v.s.\; p_T\) for 70–90% centrality with template fits from STARLIGHT

\[ \frac{d\sigma}{dy}_{\text{coherent } J/\psi} = 0.211 \pm 0.041 \text{(stat.)} \pm 0.014 \text{(syst.) mb} \]

\[ \text{ALICE Preliminary} \]

Pb-Pb √s_{NN} = 5.02 TeV, Centrality 70-90%  
\( J/\psi \rightarrow e^+e^- , |y| < 0.9 \)

→ Extraction of the coherently photo-produced J/ψ cross section
Low $p_T$ J/$\psi$ excess

All models reproduce the data except GBW2017

Measurements towards more central collisions needed to disentangle between models and underlying mechanisms
ALICE has measured quarkonium production in pp, p–Pb, Pb–Pb and Xe–Xe collisions at LHC energies.

**pp** Quarkonium production spectra well described with QCD-based models but underlying mechanism still not settled (polarization tensions)

**p–Pb** Models face difficulties in describing consistently all results
Final-state effect needed to describe the $\psi$(2S) suppression
Positive $J/\psi$ $v_2$ similar to Pb–Pb for $p_T > 4$ GeV/$c$ → common mechanism?

**Pb–Pb** Interplay between dissociation and (re)generation mechanisms at LHC energies
Is the direct $\Upsilon$(1S) production suppressed? → need more precise measurements of CNM effects and feed-down fractions
Positive $J/\psi$ $v_2$ → charm quark thermalization?
$J/\psi$ excess at low-$p_T$ interpreted as coherent photo-production

**Perspectives:**
- New Pb–Pb data taking period that year → stay tuned!
- ALICE upgrades for Run-3: continuous readout (will in particular enhance the mid-rapidity quarkonium samples), new Muon Forward Tracker detector

Thanks