Quarkonium production in p-Pb and Pb-Pb collisions with ALICE

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Outline

- ALICE detector
- p-Pb results at \( \sqrt{s_{NN}} = 8.16 \text{ TeV} \)
  - Rapidity, \( p_T \) and centrality dependence of quarkonium (J/\( \psi \), \( \psi(2S) \) and \( \Upsilon \))
    (new J/\( \psi \) results at mid rapidity)
  - Multi-differential study of J/\( \psi \)
  - Azimuthal anisotropy of J/\( \psi \)
- Pb-Pb results at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
  - Multi-differential study of J/\( \psi \)
  - Azimuthal anisotropy of J/\( \psi \)
  - Centrality dependence of \( \psi(2S) \)
  - Rapidity, \( p_T \) and centrality dependence of \( \Upsilon(1S) \)
  - Elliptic flow of \( \Upsilon(1S) \) NEW!!
- New results on the polarization of J/\( \psi \) will be presented by Luca in the next talk
Quarkonia in ALICE are measured in two rapidity ranges:

- Central barrel: $J/\psi \rightarrow e^+e^- (|y| < 0.9)$
  - Electrons tracked using ITS and TPC
  - Particle identification: TPC (+TOF)

- Forward muon arm: $J/\psi \rightarrow \mu^+\mu^- (2.5 < y < 4)$
  - Muons identified and tracked in the muon spectrometer

Acceptance coverage in both $y$ regions is down to zero $p_T$.

The ALICE results presented in this talk refer to inclusive $J/\psi$. 

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Electrons tracked using ITS and TPC
Particle identification: TPC (+TOF)

Forward muon arm: $J/\psi \rightarrow \mu^+\mu^- (2.5 < y < 4)$

Muons identified and tracked in the muon spectrometer
p-Pb
cold nuclear matter effects:
shadowing/CGC, energy loss...
p-Pb collisions in ALICE

→ To understand Cold Nuclear Matter (CNM) effects such as nuclear parton shadowing/color glass condensate, energy loss and comovers absorption

→ No Quark-Gluon Plasma (QGP) is expected in pA collisions.

→ The measurement of CNM effects in pA collisions is important to quantify the QGP effects in AA collisions

→ ALICE has collected p-Pb data at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV

→ ALICE data are collected with two beam configurations: p-Pb and Pb-p, with $\Delta y = +/- 0.465$
Nuclear modification factor: $R_{pPb}$

- Stronger suppression is observed at forward rapidity, while $R_{pPb}$ is compatible with unity both at mid and backward rapidity.

- Models based on different shadowing implementations, CGC, energy loss, transport models and comovers fairly describe the data.

\[ R_{pPb}^{J/\psi} = \frac{Y_{pPb}^{J/\psi}}{\langle T_{pPb} \rangle \sigma_{pp}^{J/\psi}} \]
\( J/\psi \ R_{pPb} \ vs \ p_T \) at \( \sqrt{s_{NN}} = 8.16 \ \text{TeV} \)

- \( R_{pPb} \) shows a \( p_T \) dependence, with an increase from low to high \( p_T \) at both forward and backward rapidity.
- At mid rapidity \( R_{pPb} \) is compatible with unity with almost no \( p_T \) dependence.
- Run2 results are more precise than the Run1 measurements at \( \sqrt{s_{NN}} = 5.02 \ \text{TeV} \) [JHEP 06 (2015) 55].
- Uncertainties on the theoretical predictions are large compared to data.
We use the symbol $Q_{pPb}$ instead of $R_{pPb}$ for nuclear modification factor due to potential bias from the centrality estimator.

Two sets of Zero Degree Calorimeters (ZDC) have been used for the centrality estimation.

$Q_{pPb}$ decreases slightly from peripheral to central collisions at forward rapidity, while trend is opposite at backward-\(y\).
Clear evolution of $Q_{pPb}$ vs $p_T$ in different centrality classes

At backward rapidity, enhancement in most central collisions for $p_T > 3$ GeV/c

At forward rapidity, stronger suppression at low $p_T$ in most central collisions and $Q_{pPb}$ is compatible with unity for $p_T > 7$ GeV/c within uncertainties for all centrality intervals
Multi-differential $J/\psi$ $Q_{pPb}$ compared to theoretical models

- In central collisions:
  - shadowing predicts a weaker $p_T$ dependence w.r.t. the one observed in data
  - energy loss predicts an increase of $Q_{pPb}$ with a different steepness than the measured one

- In peripheral collisions:
  - both theory models show no $p_T$ dependence, consistent with the $Q_{pPb}$ measurement, within uncertainties

- The models cannot describe simultaneously all aspects of $J/\psi$ suppression (rapidity, $p_T$ and centrality)
Azimuthal anisotropy ($v_2$) of $J/\psi$

- In a strongly-interacting medium, pressure gradients convert any initial spatial anisotropy into a momentum anisotropy.

- Anisotropy is quantified by the 2\textsuperscript{nd} order coefficient $v_2$ of the Fourier expansion of the particle azimuthal distribution:

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos (n(\phi - \Psi_n)) \right)$$

$$v_n = \langle \cos (n(\phi - \Psi_n)) \rangle$$

- Observation of non-zero $v_2$ in p-Pb for $p_T > 3$ GeV/c!
- Total significance (forward + backward, 5.02+8.16 TeV, 3 < $p_T$ < 6 GeV/c) ~ 5$\sigma$
- Values are similar to the ones obtained in Pb-Pb for $p_T > 3$ GeV/c.
- In Pb-Pb collisions, non-zero $J/\psi$ $v_2$ suggests charm quark participation to the collective expansion of the system.
- Common mechanism in p-Pb and Pb-Pb?
ψ(2S) suppression is stronger than the J/ψ one, especially at backward rapidity.

- Theoretical predictions based on shadowing and energy loss cannot describe the stronger ψ(2S) suppression.
- Models including final-state effects reproduce ψ(2S) behaviour at both forward and backward rapidity.
- Similar $\Upsilon(1S)$ suppression at forward and backward rapidity
- $\Upsilon(1S)$ and $J/\psi$ $R_{pPb}$ agree within ~ 1σ both at forward and backward rapidity
- Theoretical predictions based on shadowing and energy loss describe the forward rapidity results but slightly overestimate the backward rapidity results
- $\Upsilon(2S)$ suppression is consistent with $\Upsilon(1S)$ but a small hint of being more suppressed (as also observed by CMS and ATLAS at mid-$y$, and by LHCb at forward-$y$)
\[ \Upsilon(1S) \, R_{p\text{Pb}} \, \text{vs} \, p_T \, \text{at} \, \sqrt{s_{\text{NN}}} = 8.16 \, \text{TeV} \]

- Similar behaviour at both forward and backward rapidity with a hint of a stronger suppression at low \( p_T \)
- Theoretical predictions based on shadowing describe the forward rapidity results but slightly overestimate the backward rapidity results
Pb-Pb

hot matter effects: suppression vs regeneration
\[ R_{AA}^{J/\psi} \text{ in Pb-Pb collisions at } \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

- Forward-\(y\) J/\(\psi\) suppression measured precisely in fine bins of centrality
- Clear J/\(\psi\) suppression with almost no centrality dependence for \(N_{\text{part}} > 100\)
- Weaker low-\(p_T\) suppression measured by ALICE compared to PHENIX
- Different behaviour in RHIC and LHC \(R_{AA}\) is related to the interplay of suppression and regeneration mechanisms

\[ R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle} \sigma_{pp}^{J/\psi} \]
Comparison with theoretical models

- All models fairly describe the data but large uncertainties associated to charm cross section and shadowing
- Precise charm cross section measurement and more differential analyses needed
Multi-differential $J/\psi R_{AA}$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- Constraints to the theoretical models can be imposed by more differential $R_{AA}$ studies

- The suppression is stronger at high $p_T$ and for central collisions

- $R_{AA}$ decreases by 60-80% at large $p_T$ and for most central collisions

- TM1 prediction agrees with data within uncertainties
Elliptic ($v_2$) and triangular ($v_3$) flow of J/ψ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- J/ψ $v_2$ at mid-y shows agreement with forward-y result within uncertainties
- Non-zero J/ψ $v_2$ is consistent with that of open-charm mesons
- The transport model predictions are not able to describe the data in higher $p_T$ region
- A significant fraction of the observed J/ψ comes from charm quarks thermalized in the QGP
- First observation of positive J/ψ $v_3$ in Pb-Pb collisions (3.7 $\sigma$ significance)
- $v_3$ is sensitive to fluctuations of initial nucleon distributions in the overlap region
• $\psi(2S)$ shows a stronger suppression, in semi-central and central collisions, than the $J/\psi$ one

• However, the low significance limits the precision of the measurements
  [95% CL is provided for bins with too low significance]

• Results are compatible with CMS

• The 2018 data sample with ~ 3 times increase in statistics will give more precise measurement, stay tuned!
- The suppression is stronger in central collisions than in peripheral events.
- $R_{AA}$ does not show a significant dependence on $p_T$ and $y$.
- Amount of direct $\Upsilon(1S)$ suppression is an open question since feed-down fraction to $\Upsilon(1S)$ is not precisely known.
- Transport models describe the results with and without a regeneration component within uncertainties.
- Only upper edge of hydro-dynamical model agrees with data.
Elliptic flow ($v_2$) of $\Upsilon$(1S) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- $\Upsilon$(1S) $v_2$ is compatible with zero and with the small values predicted by the available theoretical models within uncertainties.
- Excluding low $p_T$, $\Upsilon$(1S) $v_2$ is $2.6 \sigma$ lower with respect to that of inclusive J/$\psi$.
- This $\Upsilon$(1S) result includes both 2015 and 2018 Pb-Pb data sets. This is the first result coming out of this new data set.

- The Kent State University (KSU) model calculations consider only the path-length dissociation of initially-created bottomonia inside the QGP medium.
- The Texas A&M University (TAMU) model incorporates in addition a regeneration component originating from the recombination of thermalized bottom quarks.
Conclusions

- We have shown quarkonium production results measured in p-Pb and Pb-Pb collisions.
- Run2 results increased significantly the precision of the measurements.
- Models face difficulties in describing consistently all results.

**p-Pb:**

- $J/\psi$ shows a stronger suppression at forward-$y$ than at backward-$y$, where $R_{\text{pPb}}$ is compatible with unity.
- Theoretical models based on CNM effects qualitatively describe $J/\psi$ results.
- $\psi(2S)$ shows a stronger suppression than $J/\psi$, final-state effects needed to explain the $\psi(2S)$ behaviour.
- Similar $\Upsilon(1S)$ and $\Upsilon(2S)$ suppression at backward and forward-$y$.
- Shadowing and energy loss models describe $\Upsilon(1S)$ behaviour at forward-$y$ results while they overestimate backward-$y$ results.

**Pb-Pb:**

- $J/\psi R_{\text{AA}}$ at LHC shows an interplay of suppression and (re)generation.
- Differential $R_{\text{AA}}$ results put strong constraints on the models.
- Non zero $J/\psi$ elliptic flow agrees with regeneration picture.
- Clear suppression of $\Upsilon(1S)$ with no indication of a significant regeneration component.
- $\Upsilon(1S) v_2$ is compatible with zero and with the current model predictions within uncertainties.
Thank you
Comparison with theoretical models

- All models fairly describe the data but large uncertainties associated to charm cross section and shadowing
- Precise charm cross section measurement and more differential analyses needed
The $\psi(2S)$ suppression is stronger than $J/\psi$ one, especially at backward rapidity.

At forward rapidity the $Q_{pPb}$ of $\psi(2S)$ follows the same trend as $J/\psi$ while at backward rapidity trend is different.

At backward rapidity, final-state effects needed to explain the $\psi(2S)$ behaviour. Some discrepancies between the data and the model in the peripheral region.
Almost no centrality dependence of $Q_{pPb}$ both at forward and backward rapidity

A hint for a stronger suppression at forward rapidity
No significant $\sqrt{s}$-dependence also at mid-rapidity, confirming observation at forward-$y$.

Small $R_{AA}$ increase in most central collisions, wrt forward-$y$, as expected in a (re)generation scenario (but fluctuations cannot be yet excluded).
Run2 analysis with increased luminosity ($L_{\text{int}}(2016) = 256 \text{ } \mu \text{b}^{-1}$, $L_{\text{int}}(2013) = 51 \text{ } \mu \text{b}^{-1}$) shows increased precision.

$R_{\text{pPb}}$ increases with $p_T$.

No centrality dependence of $Q_{\text{pPb}}$ is observed.
• Theoretical models based on shadowing and/or energy loss, CGC and comovers are in fair agreement with the data
Azimuthal anisotropy ($v_2$) of $J/\psi$ in p-Pb collisions

Low multiplicity
Clear away-side correlation presumably due to recoil jet

High multiplicity
Additional enhancement at both near and away sides

Low multiplicity
High multiplicity
Jet correlations eliminated via subtraction

- $p_T < 3 \text{ GeV/c} \rightarrow v_2$ compatible with 0
  In line with expectation of no recombination
- $3 < p_T < 6 \text{ GeV/c} \rightarrow v_2 > 0$
  Total (forward+backward, 5.02+8.16 TeV) significance about 5$\sigma$
  Values comparable to the measurements in central Pb-Pb collisions