Quarkonium and heavy-flavour measurements with ALICE at the LHC

Indranil Das
(for the ALICE Collaboration)
Saha Institute of Nuclear Physics
Science and Engineering Research Board, India
Motivation

- Nuclear matter at extreme energy density forms a Quark-Gluon Plasma
- Heavy quarks are produced at the first instant of collisions
- Interact with the hot and dense QCD medium
  - Quarkonium
    - Suppression due to colour screening
    - (Re)generation during the QGP evolution or at the phase boundary
    - Elliptic flow
  - Heavy-Flavour
    - Collisonal and radiative energy loss
    - Energy loss dependence on a) medium density, b) colour charge and c) quark mass
- Cold Nuclear Matter effects
  - Nuclear parton shadowing/gluon saturation
  - Parton energy loss
  - Nuclear break-up

References:
- Andronic et al., EPJ C 76 (2016) 107
- Matsui and Satz, PLB 178 (1986) 416
- Poskanzer and Volosin, PRC 58 (1998) 1671
- Djordjevic et al., NPA 783 (2007) 493

Quarkonia:
- Ashik Ikbal Sheikh
- Bharati Naik
- Renu Bala
- Samrangy Sadhu
- Sudhir Pandurang Rode

Heavy-Flavour:
- Anisa Khatun
- Dhananjaya Thakur
- Hushnud
- Wadut Shaikh

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Conference title
ALICE at the LHC: DEUTHER 2018, I. Das
# A Large Ion Collider Experiment

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>$\sqrt{s_{\text{NN}}}$ (TeV)</th>
<th>$L_{\text{int}}$ (*)</th>
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<tr>
<td>pp</td>
<td>2009-13</td>
<td>0.9, 2.76, 7, 8</td>
<td>200 $\mu$b$^{-1}$, 100 nb$^{-1}$</td>
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<tr>
<td></td>
<td>2015-17</td>
<td>5.02</td>
<td>1.3 pb$^{-1}$</td>
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<tr>
<td></td>
<td>2015-18</td>
<td>13</td>
<td>35 pb$^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2013</td>
<td>5.02</td>
<td>15 nb$^{-1}$</td>
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<tr>
<td></td>
<td>2016</td>
<td>5.02, 8.16</td>
<td>3 nb$^{-1}$, 25 nb$^{-1}$</td>
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<td>Xe-Xe</td>
<td>2017</td>
<td>5.44</td>
<td>0.3 $\mu$b$^{-1}$</td>
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<td>Pb-Pb</td>
<td>2010,11</td>
<td>2.76</td>
<td>75 $\mu$b$^{-1}$</td>
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<tr>
<td></td>
<td>2015</td>
<td>5.02</td>
<td>250 $\mu$b$^{-1}$</td>
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<tr>
<td></td>
<td>2018</td>
<td>5.02</td>
<td>536 $\mu$b$^{-1}$</td>
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</table>

* Approximate value of luminosity recorded in ALICE

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Quarkonium and heavy-flavour measurements with ALICE at the LHC, DAE HEP 2018, I.Das

\[ p \rightarrow p \]
The production cross section of heavy quarks as measured in ALICE agrees with the world data.

The heavy quark cross section increases as a function of $\sqrt{s}$ in agreement with the theory calculation.

The differential production cross section of heavy-flavour also agrees with theory calculations within uncertainties.
Quarkonium production in pp collisions

- An extensive quarkonium study at various energies, thanks to LHC and stable ALICE data taking.
- The model prediction for the $\psi(2S)/J/\psi$ cross section slope does not cover the low-$p_T$ otherwise in agreement with data.
- CGC+NRQCD based model is now able to properly describe the low $p_T$ region.
Quarkonium production in pp collisions

- CGC+NRQCD based model is now able to properly describe the low $p_T$ region.
- The cross section ratio for $\psi(2S)/J/\psi$ is found to be independent of colliding energy as a function of $p_T$ and rapidity.
- The 2S/1S cross section ratio shows an increasing trend with $p_T$ and no rapidity dependence.
- ALICE results are in agreement with other LHC experiments (shown only for $\Upsilon$ production).
Quarkonium and heavy-flavour measurements with ALICE at the LHC, DAE HEP 2018, I. Das
Quarkonium production in p-Pb

- Stronger suppression of $J/\psi$ is observed at forward rapidity, while $R_{pPb}$ is compatible with unity at backward rapidity.
- ALICE and LHCb results are in agreement.
- Models based on different shadowing implementations, CGC, energy loss, transport models and comovers fairly describe the data.
- The $p_T$ dependence of $R_{pPb}$ shows an increase from low to high $p_T$ at both forward, mid and backward rapidity.
Quarkonium production in p-Pb

- A similar suppression as for $J/\psi$ is observed at forward rapidity for $\psi(2S)$ and $\Upsilon(1S)$. The $J/\psi$ and $\Upsilon(1S)$ $R_{pPb}$ are compatible with no modification at backward rapidity.
- At backward rapidity, final-state effects needed to explain the $\psi(2S)$ behaviour.
- The $p_T$ dependence of $\Upsilon$ $R_{pPb}$ shows an increase from low to high $p_T$ at both forward and backward rapidity, where the model prediction suggests flat distribution.
Quarkonium flow in p-Pb

- Angular correlations between forward and backward $J/\psi$ and charged hadrons separated by rapidity gap of at least 1.5.
- Similar long range correlation as observed for double ridge structure at $\Delta \phi = 0$ and $\Delta \phi = \pi$.
- A significance of $5\sigma$ reported for the $v_2$ measured between 3 and 6 GeV/c.
- The $J/\psi$ $v_2$ measured for p-Pb is comparable to that in Pb-Pb although the underlying mechanism is not known to be also same or different.
- The transport model calculations give very small $v_2$ over the full $p_T$ range.
The nuclear modification factor is compatible with unity at forward rapidity.

The $R_{pPb}$ of heavy-flavor decay muons at high $p_T$ is also compatible with unity at backward rapidity, but above unity by more than $2\sigma$ in $2.5 < p_T < 3.5$ GeV/c.

The NLO calculation with shadowing can reproduce the data at both forward and backward rapidity.

The coherent scattering model based on CNM energy loss and $k_T$ broadening can explain the forward rapidity $R_{pPb}$, while for backward rapidity incoherent multiple scattering models can reproduce the data.
Heavy-flavour production in p-Pb

- The average $R_{pPb}$ of prompt $D^0, D^+$ and $D^{**}$ mesons is compatible with unity and can be explained by the theoretical calculations that include initial-state effects.
- The $v_2$ of heavy-flavour decay electrons in high-multiplicity events are above $5\sigma$ significance and found similar to those of forward rapidity heavy-flavour decay muons.
- The $R_{pPb}$ of beauty-hadron decay to electron is compatible with unity for $1 < p_T < 8$ GeV/c.

Further: oral presentation by Bharti and Renu and poster presentation by Ashik
Quarkonium and heavy-flavour measurements with ALICE at the LHC, DAE HEP 2018, I.Das
• \( J/\psi \) suppression is visible at RHIC whereas at the LHC there is an interplay of suppression and (re)generation.
• Most precise result in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) and similar to that at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \).
• The \( J/\psi \) \( R_{AA} \) is found to be of similar magnitude for Pb-Pb and Xe-Xe collisions at forward rapidity, however no suppression is observed at mid-rapidity for Xe-Xe.
• A stronger suppression factor \( \left( \frac{R_{PbPb}}{R_{pPb} \times R_{Pbp}} \right) \) is found at high-\( p_T \) by combining the \( J/\psi \) p-Pb and Pb-Pb forward rapidity results.
Quarkonium predictions in Pb-Pb

- $p_T > 0.3$ GeV/$c$ to suppress the contribution from photo-production
- The brackets represent the remaining contribution

- All models can describe the data but with larger uncertainties.

**Statistical Hadronization**:
Andronic et al., Nucl. Phys. A 904-905 (2013) 535c

**Co-movers interaction model**:

**Transport model (TM1)**:

**Transport model (TM2)**:
A strong rapidity dependence is measured for \( J/\psi R_{AA} \) which shows a trend opposite to that of shadowing predictions.

The multi-differential measurement of \( J/\psi R_{AA} \) as a function of centrality, \( p_T \), and rapidity is ongoing and will provide more insight into the interplay between suppression and (re)generation in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \).
Quarkonium in Pb-Pb

arXiv: 1805.04387

- Transport models by Zhou et al. (TM2) and Rapp et al. (TM1) and the anisotropic hydrodynamic model by Strickland et al. qualitatively reproduce the centrality dependence.
- The anisotropic hydrodynamic model by Strickland et al. can describe the rapidity dependence of $R_{AA}$, but hint of different trend is observed.
- The $p_T$ dependence of $\Upsilon(1S)$ $R_{AA}$ in Pb-Pb collisions is described by the transport model and anisotropic hydrodynamics model.
- Transport model, with or without (re)generation effect can describe the data.
- The ratio of $R_{AA}$ for $\Upsilon(2S)$ to $\Upsilon(1S)$ is $0.28\pm0.12$ (stat.)$\pm0.06$ (sys.) $\rightarrow$ sequential suppression.
Both the bound state charmonium and prompt open-charm mesons show non-zero elliptic flow.

The transport model predictions are not able to describe the data in the high $p_T$ region.

A non-zero $v_3$ of $J/\psi$ ($3.7\sigma$ significance) has been measured for the first time.
Heavy-flavour production in Pb-Pb

- A strong suppression is observed for the heavy-flavour muon $R_{AA}$ for central collisions.
- A positive heavy-flavour $v_2$ is measured using scalar product and two particle Q cumulants in semi-central collisions with more than 3σ significance for $3 < p_T < 5$ GeV/c.
- The model predictions based on Boltzmann (BAMPS) and Langevin (TAMU) transport equations consider collisional energy loss, they can explain the elliptic flow measurements.
- Both results can be also explained by MC@sHQ+EPOS which considers collisional and radiative energy loss.
Heavy-flavour in Pb-Pb

A strong suppression is observed for the D-meson $R_{AA}$ for central collisions and $p_T > 3$ GeV/c.

The elliptic flow is stronger in the interval $2 < p_T < 4$ GeV/c.

The $R_{AA}$ and $v_2$ observables together set stringent constraints to model calculations and charm diffusion coefficient.

Further: poster presentation by Sudhir and Samrangy
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Quarkonium as a function of multiplicity in pp

- Finite spatial extension (non-zero impact parameter) for elementary parton-parton interactions.
- Formation of colour ropes or flux tubes—strings.
- $N_{\text{collisions}}^{\text{parton-parton}} \propto N_{\text{strings}}$.
- Strings can overlap in transverse direction resulting in a reduction of soft-particle production, $\frac{dN_{\text{ch}}}{d\eta} \sim \sqrt{N_{\text{strings}}}$.
- Hard particle production, $N_{J/\psi} \propto N_{\text{coll}} \propto N_{\text{strings}}$.
- The high multiplicity pp events are similar to pA.
- NA3 and E866 collaboration results used for:
  $R_{J/\psi}^{pA} = N_{\text{coll}} A^{\alpha - 1}$ [$\alpha = 0.95$ from E866]
- Compilation of various hadron-nuclear results [NPA395(1983)482] :
  $R_{h}^{pA} = 1 + \beta (N_{\text{coll}} - 1)$ with $[0.5 < \beta < 0.65]$
- Finally using, $N_{\text{coll}} \approx \frac{\sigma_{pp}}{\pi r_{0}^{2}} A^{1/3}$ for pA collisions, the dependency is extracted for $R_{J/\psi}^{pA} \propto R_{h}^{pA}$ and applied for pp collisions.
A detailed study has been performed to explore the rapidity dependence at various energies for different colliding systems and different resonances.

A linear increase has been observed for forward rapidity $J/\psi$ vs mid-rapidity multiplicity compared to the faster than linear increase of midrapidity $J/\psi$ with multiplicity in mid-rapidity.

The increase of the bottom production as function of charged particle multiplicity is found to be similar to that observed for charm production. Similar observation in di-electron spectra.
Heavy-quark as a function of multiplicity in p-Pb

- An increase of $J/\psi$ yield with normalized $\frac{dN_{ch}}{d\eta}$ is observed at backward rapidity, however in forward rapidity a hint of saturation is observed.
- The normalized $J/\psi < p_T >$ increases at low charged-particle multiplicity and saturates at high multiplicity events.
- A similar increase for heavy-flavour production has been measured as a function of charged-particle multiplicity.
Summary

• pp collisions
  • ALICE results are in agreement with the other LHC experiments and world data.
  • Theoretical calculations start to describe data over all $p_T$ but polarisation is still a puzzle.

• p-Pb collisions
  • The nuclear modification factor can be explained by Cold Nuclear Matter effects.
  • A long-range correlation is observed: $J/\psi$ $v_2$ in central p-Pb collisions.

• Heavy-ion collisions
  • Interplay of two main mechanisms: suppression and (re)generation for charmonium, whereas for bottomonium suppression plays dominant role with negligible (re)generation.
  • Observation of non-zero $v_2$ with higher precision and first look at non-zero $v_3$ for $J/\psi$.
  • A strong energy loss of open heavy flavours in central collisions.
  • The elliptic flow measurement of heavy-flavour together with $R_{AA}$ set stringent constraints for modes.

• Heavy-quark as a function of multiplicity
  • The increase of quarkonium production as a function of charged-particle multiplicity exhibits no strong $\sqrt{s}$ dependence and also found to be similar for charmonium and bottomonium.
  • An increase of bottom quark production compared to charm is observed in dielectron spectra for $p_T > 3$ GeV/c.
  • The production of D mesons shows a similar increase with charged-particle multiplicity.
ALICE upgrade

- ALICE is entering LS2 upgrade.
- ALICE will be able to collect pp and p-Pb data at 200 kHz and Pb-Pb 50 kHz in Run3 of LHC.
- ALICE plans to collect 10 nb$^{-1}$ of Pb-Pb data for a detailed understanding of QGP.
Thank you
Prompt, non-prompt and feed-down

In addition to (10-30)% B-decay production

Charmonium [A. Andronic et al., EPJC 76 (2016) 107]

Bottomonium

![Pie charts showing production fractions for different pT ranges.](image-url)
Predictions for charmonium $v_2$ in p-Pb

![Graph showing $v_2$ vs. $p_T$ for charmonium in p-Pb collisions at 8.16 TeV mid-rapidity for 02-10% centrality. The graph includes data from ALICE and CMS for $J/\Psi$ and $\Upsilon(2S)$.]
6.) Charm in pA Collisions:

- $R_{pA}$ data consistent with shadowing

  But: large $v_2$

- Collectivity?

- small c-quark $v_2$

- very similar for charmonia

[R. Vogt]

[H. Li]

[Du+RR'18]