'ϒ' production in p-Pb and Pb-Pb collisions with ALICE at the LHC

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Abstract
ALICE (A Large Ion Collider Experiment) is devoted to the study of heavy-ion collisions at LHC energies. In such collisions a deconfined state of nuclear matter, the Quark-Gluon Plasma (QGP), is formed. Due to their early production, quarkonium states are good probes to study the QGP evolution. Such states are affected by suppression mechanisms which lead to reduced yields with respect to pp and p-Pb collisions, while regeneration phenomena might lead to an enhancement of their production. The latter effects are expected to be negligible at LHC for bottomonium states. The recent ALICE results on 'ϒ' production in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV will be presented and compared with previous measurements at \( \sqrt{s_{NN}} = 2.76 \) TeV. A comparison with theoretical calculations will be performed as well. Results obtained in p-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV will also be discussed.

Keywords: Quarkonium, Upsilon, High energy physics

1. Motivations for quarkonium study
Quarkonium states are formed early during Quark Gluon Plasma (QGP [1]), hence they cross the whole QGP evolution probing the medium created in the collisions. Colour screening effects, sequential suppression and regeneration phenomena are the mechanisms affecting quarkonium production in the QGP [2–4]. Bottomonium mesons are bound states of b quark and antiquark. Bottomonium is a good candidate for the study of QGP since, with respect to lower mass quark bound states:
- the perturbative theoretical approach is more reliable since bottom quark mass is higher;
- it presents no feed down from open bottom flavoured states;
- the regeneration is less relevant [5];
- Cold Nuclear Matter (CNM) effects are expected to be smaller.
Moreover bottomonium states study is complementary to the study of charmonium states since they allow to study a different Bjorken-x range. The modifications of quarkonium production yields, in heavy ion collisions, is evaluated through the nuclear modification factor \( R_{AA} \). The \( R_{AA} \), defined in (1), is the ratio between the production cross section measured in A-A collisions and in pp collisions (\( \sigma_{pp} \)) rescaled by the nuclear overlap function \( \langle T_{AA} \rangle \).

\[
R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \cdot \sigma_{pp}} \quad (1)
\]

ALICE [6] has already published results in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV [7]. The \( R_{AA} \) has been computed using the \( \sigma_{pp} \) value evaluated using measurements by the LHCb Collaboration [8]. 'ϒ(1S)' results presented a centrality dependence of \( R_{AA} \), with stronger suppression in the most central events. ALICE results are also compatible with CMS \( R_{AA} \) measured at mid rapidity [9].

2. Experimental setup
ALICE is composed by two groups of detectors: the central barrel and the muon spectrometer. Detectors
from both groups have been used for this analysis. A
detailed description of the whole apparatus can be found
in [6, 10]. The interaction vertex identification has been
performed using the two silicon pixel layers of the six
layers of silicon detectors composing the Inner Tracking
System (ITS) [11]. The minimum bias trigger is pro-
vided by the V0 [12], a group of two arrays of scintilla-
tors, placed in the pseudo-rapidity ranges \(2.8 < \eta < 5.1\)
(V0-A) and \(-3.7 < \eta < -1.7\) (V0-C). The centrality
estimation is obtained trough a Glauber fit of the
V0 raw signal amplitudes [12, 13]. The two Zero De-
gree Calorimeters (ZDC) [10], installed at \(\pm 114\) m from
the Interaction Point in the accelerator tunnel, are used
to reject electromagnetic events and to remove beam-
induced background. The muon spectrometer system
is located at the Interaction Point in the accelerator tunnel, are used
to reject electromagnetic events and to remove beam-
induced background. The muon spectrometer system
[14] is located at \(-4 < \eta < -2.5\) and is specifically de-
signed to track and identify muons. The innermost com-
ponent is a ten radiation length thick front absorber. The
muon tracker consists of five tracking stations, com-
posed by two planes of cathode pad chambers each. It
extends through a dipole which provides 3T · m in-
tegrated magnetic field to bend the charged particles tra-
jectory. Downstream to the tracking system a 1.2 m
thick (7.2 interaction lengths) iron wall stops e-
light hadrons coming from \(\pi\) and \(K\) mesons decays.
The muon trigger system [15], made of four planes of
x-y reading RPC chambers, allows for online trigger-
ing on single muons and dimuons and for offline muon
identification by matching with the tracker tracks [16].
An additional absorber is placed around the beam line
along the whole muon spectrometer length.

3. Analysis strategy and data sample

The \(\Upsilon(1S)\) yields are obtained fitting a \(\mu^+\mu^-\) invariant
mass spectrum. The tracks of the muon tracker which
are matched in the muon trigger are flagged and iden-
tified as muons. The muons used for the computation
of the invariant mass spectrum are selected by applying
cuts tuned to maximise the signal to background ratio.
The cuts are:

- \(-4 < \eta_{\mu} < -2.5\) to select muons within acceptance
  of the spectrometer;

- \(p_{T\mu} \geq 2\) GeV/c to reduce combinatorial back-
  ground;

- \(17.6\) cm \(< R_{abs} < 89.5\) cm, where \(R_{abs}\) is the radial
  position of the track at the front absorber end, to
  reduce the contribution of particles from beam gas
  interactions.

A \(-4 < y_{\mu\mu} < -2.5\) cut is applied on the dimuon ra-
pidity. The fit of the invariant mass spectrum is per-
formed with a function composed by the sum of one Ex-
tended Crystal Ball (CB2) for each resonance and a phe-
nomenological background shape chosen among double
or single exponentials or power laws. The presented re-
sults have been obtained in p-Pb and Pb-Pb collisions
at \(\sqrt{s_{NN}} = 5.02\) TeV. Since p-Pb collisions have been
performed both with the proton or the Pb nucleus go-
ing towards the muon spectrometer, two rapidity ranges
have been studied. The integrated luminosity values are
reported in Table 3. The \(\sigma_{pp}\) reference has to be mea-
sured at \(\sqrt{s} = \sqrt{s_{NN}}\) in order to compute the \(R_{AA}\) value.
The low luminosity collected by ALICE in pp collisions at
\(\sqrt{s} = 5.02\) TeV prevents the evaluation of the \(\sigma_{pp}\)
reference, hence the cross section value has been com-
puted by interpolating ALICE data at \(\sqrt{s} = 7\) and \(8\) TeV
[17, 18] and LHCb data at \(\sqrt{s} = 2.76, 7\) and \(8\) TeV
[8, 19]. The interpolation method is described in detail in
[20].

4. p-Pb results

The p-Pb collisions are a CNM reference. Both for-
ward (\(2.03 < y_{cms} < 3.53\)) and backward (\(-4.46 <
\quad y_{cms} < -2.96\)) rapidity regions have been studied using
inverse beam configurations. At backward rapidity (Pb-
going side) the \(R_{pA}\) values are compatible with no sup-
pression, while at forward rapidity the results present a
better agreement with models which foresee a reduction
of the \(\Upsilon\) yields [21–24]. The comparison of data with
models suggests a better compatibility of experimental
results with energy-loss only models at backward ra-
pidity, while at forward rapidity the best agreement has
been found with models containing both energy loss and
NLO nuclear shadowing as shown in Fig.1. At back-
ward rapidity the data suggests the models are overest-
mating the anti-shadowing contribution.

5. Pb-Pb results

The presented \(R_{AA}\) measurements at \(\sqrt{s_{NN}} =
5.02\) TeV have been obtained analysing invariant mass

| Beam configuration | \(\sqrt{s_{NN}}\) | \(L_{int}\) |
|-------------------|-----------------|-------------|
| p-Pb              | 5.02 TeV        | 5.00 nb \(^{-1}\) |
| Pb-p              | 5.02 TeV        | 5.8 nb \(^{-1}\) |
| Pb-Pb             | 5.02 TeV        | 225 \(\mu\)b \(^{-1}\) |

Table 1: Integrated luminosity for different beam configurations
spectra with a total of \(N_{\Upsilon(1S)} = 1107 \pm 70(\text{stat.}) \pm 43(\text{syst.})\) reconstructed \(\Upsilon(1S)\) mesons, which corresponds to 10 times the \(\Upsilon(1S)\) statistics collected at \(\sqrt{s_{NN}} = 2.76\) TeV. The systematic uncertainties are mainly due to signal extraction (8 – 20%), \(T_{\text{AA}}\) evaluation (1 – 3%) and tracker and trigger efficiencies (4 – 7%). The centrality dependence of \(R_{\text{AA}}\) is qualitatively similar to the one observed at \(\sqrt{s_{NN}} = 2.76\) TeV as observed in Fig.2. Even if the \(R_{\text{AA}}\) computed at \(\sqrt{s_{NN}} = 5.02\) TeV is systematically above \(R_{\text{AA}}\) computed at \(\sqrt{s_{NN}} = 2.76\) TeV the two values are compatible within uncertainties (see Fig.2). The experimental data have been compared with two transport models (see Fig.3). The Emerick model [5] includes regeneration mechanisms, tuned on LHCb \(b\bar{b}\) cross section measurement, and a feed-down contribution tuned on CDF data. The uncertainty bands have been obtained by varying the nuclear shadowing amount from 0% to 25%. The Zhou model [25] includes no regeneration, but contains CNM effects tuned on EKS98 nuclear PDFs. The uncertainty bands are obtained by varying the feed-down fractions. Both the models compared to data are qualitatively capable of reproducing the observed trend within their uncertainty bands. With the current results no firm conclusion can be given about the presence of regeneration mechanism. The rapidity dependence of \(R_{\text{AA}}\) has been measured. The trend of \(R_{\text{AA}}\) is growing from higher to lower \(y\) (Fig.4). The \(R_{\text{AA}}\) values at the two studied energies (\(\sqrt{s_{NN}} = 2.76\) and 5.02 TeV) are compatible within uncertainties. The \(R_{\text{AA}}\) values are compared with Strickland model [26] (See Fig.5). The model foresees no regeneration or CNM and includes hydrodynamic effects such as thermal suppression and anisotropic screening. The uncertainty bands are obtained through the variation of \(\eta/s\) ratio. Even if the slope suggested by experimental data seems to be opposite with respect to the one the model suggests, the agreement is still satisfied within uncertainties.

6. Conclusions

The p-Pb analysis provided no significant observation of suppression at backward rapidity, while at forward rapidity a hint of suppression of the \(\Upsilon(1S)\) production has been observed. All the tested models can reproduce within uncertainties the experimental data. In the Pb-Pb analysis a strong centrality dependence of the \(R_{\text{AA}}\) has been observed, with smaller \(R_{\text{AA}}\) at higher centralities. No firm conclusion can be given about the energy hierarchy since the data points at \(\sqrt{s_{NN}} = 2.76\) and

\(^1\text{shear viscosity-to-entropy density ratio}\)

\(^2\text{The bars represent the statistical uncertainties, the boxes around the points the systematic ones, while the box drawn at } R_{\text{pA}} \text{ or } R_{\text{AA}} \text{ represents the global uncertainty.}\)
5.02 TeV are compatible within uncertainties. Some tension on the rapidity $R_{AA}$ dependence between data and models has been observed, nevertheless the size of experimental and theoretical uncertainties prevents firm conclusions.

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