ALICE results on quarkonia

- Introduction
- Selected pp highlights
- NEW → Results from the 2011 Pb-Pb run
  - J/ψ nuclear modification factor(s), v$_2$, $\langle p_T \rangle$, ψ(2S)
- Prospects and conclusions

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LHC: a new dawn for quarkonia studies.....
Introduction (1)

- Quarkonia suppression via colour screening $\rightarrow$ probe of deconfinement (Matsui and Satz, PLB 178 (1986) 416)

- Sequential suppression of the quarkonium states (Digal, Petreczky, Satz, PRD 64 (2001) 0940150)

- Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity (Andronic, Braun-Munzinger, Redlich, Stachel, PLB 571(2003) 36)
Studies performed at SPS/RHIC energies showed a significant $J/\psi$ suppression in heavy-ion collisions (even after taking into account cold nuclear matter effects) (Brambilla et al., EPJ C71(2011) 1534)

First results from ALICE (QM2011) have shown a smaller suppression with respect to RHIC, compatible with $J/\psi$ (re)generation (ALICE coll., arXiv:1202.1383, accepted by PRL)

Today $\rightarrow$ deeper understanding thanks to the high-lumi 2011 Pb run
Experiment and data taking

Quarkonia detection

In the forward muon spectrometer (2.5 < y < 4) via $\mu^+\mu^-$ decays

In the central barrel (|y| < 0.9) via $e^+e^-$ decays

Acceptance extends down to $p_T=0$

- MB trigger based on
  - Forward scintillator arrays (VZERO)
  - Silicon pixel (SPD)

- In addition, trigger on muon (pairs) in the forward spectrometer
  ($p_T \sim 1$ GeV/c threshold for Pb-Pb 2011)

Integrated luminosity for quarkonia analysis

(up to) ~100 nb$^{-1}$ for pp
~ 70 $\mu$b$^{-1}$ for Pb-Pb
pp: selected results

- Data taking at $\sqrt{s} = 2.76$ TeV essential to build the $R_{AA}$ reference, result based on $L_{\text{int}}^e = 1.1$ nb$^{-1}$ and $L_{\text{int}}^\mu = 19.9$ nb$^{-1}$

$$\sigma_{J/\psi}(|y| < 0.9) = 6.71 \pm 1.54(\text{stat.}) \pm 1.21(\text{syst.}) + 1.01(\lambda_{HE} = 1) - 1.41(\lambda_{HE} = -1) \mu b$$

$$\sigma_{J/\psi}(2.5 < y < 4) = 3.34 \pm 0.13(\text{stat.}) \pm 0.27(\text{syst.}) + 0.53(\lambda_{CS} = 1) - 1.07(\lambda_{CS} = -1) \mu b.$$

- Results in agreement with NLO NRQCD calculations

ALICE Coll., arXiv:1203.3641
J/ψ polarization results

- Discriminate among the different theoretical models of J/ψ production
- Long-standing puzzle with CDF results

ALICE Coll., PRL 108(2012) 082001


- First result at LHC energy: almost no polarization for the J/ψ
- First theoretical calculation (NLO NRQCD) compared to data: promising result, reasonable agreement with theory
Multiplicity dependence in pp

- Highest charged particle multiplicity \( \langle dN_{\text{ch}}/d\eta \rangle \sim 30 \) in this analysis comparable with Cu-Cu collisions (50-55\%) at RHIC.

- Relative \( J/\psi \) yield increases linearly with the relative multiplicity.

- Help to understand the interplay between hard and soft interactions in the context of multi-partonic interactions (MPI), and/or underlying event.

- Model predictions (PYTHIA) do not reproduce data.

- Study ongoing with other particles, e.g. D-mesons.

Pb-Pb collision results

- Today’s menu
  - $R_{AA}$ vs $\langle N_{\text{part}} \rangle$
    - Forward rapidity (HP ’12)
    - Mid-rapidity (NEW!)
    - Forward rapidity in $p_T$ bins (NEW!)
  - $R_{AA}$ vs $p_T$
    - Forward rapidity (HP ’12)
    - Forward rapidity in centrality bins (NEW!)
    - $J/\psi \langle p_T \rangle$ and $\langle p_T^2 \rangle$ (NEW!)
  - $R_{AA}$ vs $y$ (HP ’12 + NEW!)
  - $J/\psi$ elliptic flow
    - Intermediate centrality vs $p_T$ (HP ’12)
    - $v_2$ vs centrality (NEW!)
  - $\psi(2S)/J/\psi$ ratio: Pb-Pb vs pp (NEW!)
Charmonia detection (Pb-Pb) in ALICE

Electron analysis: background subtracted with event mixing → Signal extraction by event counting

Muon analysis: fit to the invariant mass spectra → signal extraction by integrating the Crystal Ball line shape
Pb-Pb collisions: $R_{AA}$ vs $\langle N_{\text{part}} \rangle$

- Centrality dependence of the nuclear modification factor studied at both central and forward rapidities.

- At forward $y$, $R_{AA}$ flattens for $N_{\text{part}} \geq 100$.

- Large uncertainty on the (midrapidity) pp reference prevents a final conclusion on a different behaviour for central events at mid- and forward rapidity.
Pb-Pb collisions: $R_{AA}$ vs $\langle N_{\text{part}} \rangle$

- **Comparison with PHENIX**
  - Stronger centrality dependence at lower energy
  - Systematically larger $R_{AA}$ values for central events in ALICE
  - Behaviour qualitatively expected in a (re)generation scenario
    → Look at theoretical models
Pb-Pb collisions: $R_{AA}$ vs $\langle N_{part} \rangle$

**Comparison with models**

- Models including a large fraction (>50% in central collisions) of $J/\psi$ produced from (re)combination or models with all $J/\psi$ produced at hadronization can describe ALICE results for central collisions in both rapidity ranges.
$R_{AA}$ vs $\langle N_{\text{part}} \rangle$ in $p_T$ bins

- $J/\psi$ production via (re)combination should be more important at low transverse momentum

- Compare $R_{AA}$ vs $\langle N_{\text{part}} \rangle$ for low-$p_T$ ($0<p_T<2 \text{ GeV/c}$) and high-$p_T$ ($5<p_T<8 \text{ GeV/c}$) $J/\psi$

- Different suppression pattern for low- and high-$p_T$ $J/\psi$

- Smaller $R_{AA}$ for high $p_T$ $J/\psi$

Uncertainties
- uncorrelated (box around points)
- partially correlated within and between sets ([])
- 100% correlated within a set and between sets (text)
R_{AA} vs \langle N_{\text{part}} \rangle in p_T bins

- J/ψ production via (re)combination should be more important at low transverse momentum.

- Compare R_{AA} vs \langle N_{\text{part}} \rangle for low-\(p_T\) (0<\(p_T<2\) GeV/c) and high-\(p_T\) (5<\(p_T<8\) GeV/c) J/ψ.

- Different suppression pattern for low- and high-\(p_T\) J/ψ.

- Smaller R_{AA} for high \(p_T\) J/ψ.

- In the models, \~50\% of low-\(p_T\) J/ψ are produced via (re)combination, while at high \(p_T\) the contribution is negligible → fair agreement from \(N_{\text{part}}\) ~100 onwards.
As an alternative view, \( R_{AA} \) is shown as a function of the \( J/\psi \ p_T \) for various centrality bins.

- **0-90%**

- **0-20% vs 40-90%**

Suppression is **stronger for high-\( p_T \) \( J/\psi \)** (\( R_{AA} \approx 0.6 \) at low \( p_T \) and \( \approx 0.35 \) at high \( p_T \)).

Splitting in centrality bins we observe that the difference low-\( p_T \) vs high-\( p_T \) suppression is more important for central collisions.
J/\psi \ R_{AA} \ vs \ p_T

- As an alternative view, $R_{AA}$ is shown as a function of the $J/\psi$ $p_T$ for various centrality bins.

0-90%

0-20% vs 40-90%

- Suppression is stronger for high-$p_T$ $J/\psi$ ($R_{AA} \sim 0.6$ at low $p_T$ and $\sim 0.35$ at high $p_T$)

- Splitting in centrality bins we observe that the difference low $p_T$ vs high-$p_T$ suppression is more important for central collisions.

- Fair agreement data vs models with large contribution from (re)combination (slightly worse for peripheral events at low $p_T$)
The $J/\psi <p_T>$ and $<p_T^2>$ show a decreasing trend as a function of centrality, confirming the observation that low-$p_T$ $J/\psi$ are less suppressed in central collisions.

The trend is different wrt the one observed at lower energies, where an increase of the $<p_T>$ and $<p_T^2>$ with centrality was obtained.
Inclusive $J/\psi$ measured also as a function of rapidity: $R_{AA}$ decreases by 40% from $y=2.5$ to $y=4$

Suppression increases with centrality and it is stronger in the most forward region
Inclusive J/$\psi$ measured also as a function of rapidity: $R_{AA}$ decreases by 40% from $y=2.5$ to $y=4$

Suppression beyond the current shadowing estimates. Important to measure cold nuclear matter effects (incoming pA data taking)

Suppression increases with centrality and it is stronger in the most forward region

Comover+regeneration model seems to predict a weaker rapidity dependence
The contribution of $J/\psi$ from (re)combination should lead to a significant elliptic flow signal at LHC energy.

Analysis performed with the EP approach (using VZERO-A).
Correct $v_2^{obs}$ by the event plane resolution, $v_2 = v_2^{obs}/\sigma_{EP}$ ($\sigma_{EP}$ measured by 3 sub-events method).
Checks with alternative methods performed.
Non-zero \( J/\psi \) elliptic flow at the LHC

- **STAR**: \( v_2 \) compatible with zero everywhere
- **ALICE**: hint for non-zero \( v_2 \) in both
  - 20-60\% central events in \( 2 < p_T < 4 \) GeV/c
  - 5-20\% and 20-40\% central events for \( 1.5 < p_T < 10 \) GeV/c
- Significance up to 3.5 \( \sigma \) for chosen kinematic/centrality selections

- Qualitative agreement with transport models including regeneration
- Complements indications obtained from \( R_{AA} \) studies
ψ(2S)

- Study the ψ(2S) yield normalized to the J/ψ one in Pb-Pb and in pp.
- Charmonia yields are extracted fitting the invariant mass spectra in two $p_T$ bins: $0 < p_T < 3$ and $3 < p_T < 8$ GeV/c and, for Pb-Pb, also as a function of centrality.

- Pb-Pb: S/B (at 3 σ around the ψ(2S)) varies between 0.01 and 0.3 from central to peripheral collisions.
\( \psi(2S)/J/\psi \) double ratio

- \([\psi(2S)/J/\psi]_{\text{Pb-Pb}} / [\psi(2S)/J/\psi]_{\text{pp}}\)
- Use \( \sqrt{s} = 7 \text{ TeV} \) pp data as a reference
  (small \( \sqrt{s} \)- and \( y \)-dependence \( \rightarrow \) accounted for in the systematic uncertainty)

- Main systematic uncertainties (some sources cancel)
  - Signal extraction
  - MC inputs for acceptance calculation

- Large statistics and systematic errors prevent a firm conclusion on the \( \psi(2S) \) enhancement or suppression versus centrality

- Exclude large enhancement in central collisions
  (uncertainty on the reference shown as colored dashed lines in the plot)
Conclusions

- ALICE has studied $J/\psi$ production in Pb-Pb collisions down to zero $p_T$
- Centrality, $p_T$ and $y$ dependence of $R_{AA}$
  - $R_{AA}$ exhibits a weak centrality dependence at all $y$ and is larger than at RHIC
  - Less suppression at low $p_T$ with respect to high $p_T$, with stronger $p_T$ dependence for central events
  - Lower energy experiments show an opposite behaviour (see $\langle p_T \rangle$ vs $\langle N_{part} \rangle$)
  - Stronger suppression when rapidity increases

- First measurement of $J/\psi$ elliptic flow at the LHC, indications of non-zero $v_2$
- Models including $J/\psi$ production via (re)combination describe ALICE results on $R_{AA}$ and $v_2$
- First look at low-$p_T$ $\psi(2S)$ in Pb-Pb at the LHC
- Next step: quantitative evaluation of cold nuclear matter effects in the p-Pb run at the beginning of 2013
Please find more details on all the topics covered in this talks in the following

Talks

R. Arnaldi (session 1D)
“J/ψ and ψ(2S) production in Pb-Pb collisions with the ALICE Muon spectrometer at the LHC”

I. Arsene (session 2D)
“J/ψ production at mid-rapidity in Pb-Pb collisions at 2.76 TeV”

H. Yang (session 7A)
“Elliptic flow of J/ψ at forward rapidity in Pb-Pb collisions at 2.76 TeV with the ALICE experiment”

Posters

M. Figueredo
“J/ψ measurements at ALICE using EMCal-triggered events”

F. Fionda
“Charmonium production in pp collisions measured with the ALICE experiment at LHC”

T. Sarkar-Sinha
“Study of single muon and J/ψ production in pp collisions at √s=2.76 TeV as a function of multiplicity with ALICE”
Backup
$R_{AA}$ vs centrality, $y$-bins

Inclusive $J/\psi$, $0<\rho_T<8$ GeV/c
Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $L = 70 \mu b^{-1}$, global syst. = $\pm 6\%$

- $2.5<y<3$
- $3<y<3.5$
- $3.5<y<4$
$R_{AA}$ vs centrality, $p_T$ bins

Inclusive $J/\psi$, 2.5$<y<$4
Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $L = 70 \mu b^{-1}$, global sys. $= \pm 6$

- $0<p_T<2$ GeV/c
- $2<p_T<5$ GeV/c
- $5<p_T<8$ GeV/c
$R_{AA}$ vs $p_T$, centrality bins

Inclusive J/$\psi$, 2.5<y<4
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV, L=70 \mu b$^{-1}$, global sys. = ±6%
$R_{AA}$ vs rapidity, central events

Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $L \approx 70 \mu b^{-1}$

- Inclusive $J/\psi$, $0<p_T<8$ GeV/c, 0%-10%, global sys. = $\pm 6\%$

Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $L \approx 15 \mu b^{-1}$

- Inclusive $J/\psi$, $|y|<0.9$ 0-10%, global sys. = $\pm 26\%$

ALICE common glob. sys. = $\pm 4.5\%$
Mid-rapidity $R_{AA}$ and shadowing

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$|y|<0.9$, $p_T >0$ GeV/$c$, $L_{int} = 15\mu$b$^{-1}$

Shadowing, EKS98, (E.Ferreiro, priv.comm.)
Shadowing, nDSg, (E.Ferreiro, priv.comm.)
$R_{AA}$: comparison with CMS
$v_2$ – centrality scan

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, 5% - 20%
$J/\psi$: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, 20% - 40%
$J/\psi$: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, 40% - 60%
$J/\psi$: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c
J/\psi p_T spectra

- Comparison with lower energy results can be carried out by studying \( \langle p_T \rangle \) and \( \langle p_T^2 \rangle \) vs centrality.
- J/\psi \( \langle p_T \rangle \) and \( \langle p_T^2 \rangle \) values are extracted from fits to \( d^2N/dydp_T \).

Relative shapes of spectra strictly related to \( R_{AA} \).

Finer binning than in \( R_{AA} \) studies possible (not limited by pp statistics).
Pb-Pb: centrality selection

- Centrality estimate: standard approach
- Glauber model fits
- Define classes corresponding to fractions of the inelastic Pb-Pb cross section
## Systematic uncertainties on $R_{AA}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp reference</td>
<td>9% (for $y,p_t$ integrated)</td>
</tr>
<tr>
<td>MC inputs</td>
<td>5%</td>
</tr>
<tr>
<td>Tracking</td>
<td>6%</td>
</tr>
<tr>
<td>Trigger</td>
<td>6.4%</td>
</tr>
<tr>
<td>Matching</td>
<td>2%</td>
</tr>
<tr>
<td>$T_{AA}$</td>
<td>3.8% (for 0-90%)</td>
</tr>
<tr>
<td>Normalization</td>
<td>2%</td>
</tr>
</tbody>
</table>

- **Type A:** uncorrelated (shown as filled box around points)
- **Type B:** partially correlated within and between sets (shown as $[]$ around points)
- **Type C:** 100% correlated within a set and between sets (global quantity for all sets)

For the $R_{AA}$ versus centrality:

- **Type A:** signal extraction
- **Type B:** uncorr. syst on pp, MC inputs, trigger, tracking, matching, $T_{AA}$
- **Type C:** normalization, corr. syst on pp
\[ A \times \varepsilon \]

Electrons

Muons
Effect of non-prompt J/ψ

Inclusive J/ψ measured in ALICE

Estimate of prompt J/ψ RAA using:
- b-fraction measured by CDF, CMS and LHCb
- Interpolation at $\sqrt{s} = 2.76$ TeV
- Different b-quenching hypothesis from $R_{AA}(B)=0.2$ to $R_{AA}(B)=1$

J/ψ from b-hadrons decays have a negligible influence on our measurements