ALICE results on quarkonia

- Introduction
- Selected pp highlights
- NEW → Results from the 2011 Pb-Pb run
  - $J/\psi$ nuclear modification factor(s), $v_2$, $\langle p_T \rangle$, $\psi(2S)$
- 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 → deeper understanding thanks to the high-lumi 2011 Pb run
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 \((p_T \sim 1\ \text{GeV}/c\) threshold for Pb-Pb 2011)

Integrated luminosity for quarkonia analysis

- (up to) \(~100\ \text{nb}^{-1}\) for pp
- \(~70\ \mu\text{b}^{-1}\) 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
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**

M. Butenschoen, A. Kniehl, arXiv:1201.1872

- 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 \((dN_{ch}/d\eta \sim 30)\) 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

B. Abelev et al., ALICE Coll., Phys. Lett. B712(2012) 165
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 $\langle N_{\text{part}} \rangle$

- **Comparison with models**
  - X. Zhao and R. Rapp, Nucl. Phys. A859 (2011) 114
  - Y. Liu, Z. Qiu, N. Xu and P. Zhuang, Phys. Lett. B678 (2009) 72
  - A. Capella et al., Eur. Phys. J. C58 (2008) 437 and E. Ferreiro, priv. com.

- **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 $\langle N_{part} \rangle$ in $p_T$ bins

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

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

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

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

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

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

- In the models, $\sim50\%$ of low-$p_T$ $J/\psi$ are produced via (re)combination, while at high $p_T$ the contribution is negligible $\rightarrow$ fair agreement from $N_{\text{part}} \sim 100$ onwards.
As an alternative view, $R_{AA}$ is shown as a function of the $J/\psi$ $p_T$ for various centrality bins.

- **0-90%**

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

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

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

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

### 0-90% vs 0-20% vs 40-90%

- **Suppression is stronger for high-\( p_T \) \( J/ψ \) (\( R_{AA} \approx 0.6 \) at low \( p_T \) and \( \approx 0.35 \) at high \( p_T \)).**
- **Splitting in centrality bins we observe that the difference low 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/ψ $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ show a decreasing trend as a function of centrality, confirming the observation that low-$p_T$ J/ψ are less suppressed in central collisions.

The trend is different wrt the one observed at lower energies, where an increase of the $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ 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.
\( J/\psi \) \( R_{AA} \) vs rapidity

- 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 $\sqrt{s} = 7$ TeV pp data as a reference (small $\sqrt{s}$- and $y$-dependence → 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 $J/\psi$, $0<p_T<8$ GeV/c

**Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $L=70$ µb$^{-1}$, global sys. $= \pm 6\%$**

**2.5<y<3**

**3<y<3.5**

**3.5<y<4**
$R_{\text{AA}}$ 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. = ±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 $J/\psi$, $2.5<y<4$

\[ \text{Pb-Pb } \sqrt{s_{NN}}=2.76 \text{ TeV}, L=70 \mu b^{-1}, \text{ global sys.} = \pm 6\% \]

- $0-20\%$
- $20-40\%$
- $40-90\%$
$R_{AA}$ vs rapidity, central events
Mid-rapidity $R_{AA}$ and shadowing
$R_{AA}$: 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
  - VZERO-A EP: inv. mass fit technique

- Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, 20% - 40%
  - J/$\psi$: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c
  - VZERO-A EP: inv. mass fit technique

- Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, 40% - 60%
  - J/$\psi$: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c
  - VZERO-A EP: inv. mass fit technique
J/ψ $p_T$ spectra

- Comparison with lower energy results can be carried out by studying $<p_T>$ and $<p_T^2>$ vs centrality.

- J/ψ $<p_T>$ and $<p_T^2>$ values are extracted from fits to $d^2N/dydp_T$.

\[
\frac{d^2N}{dydp_T} \propto \frac{p_T}{1 + \left(\frac{p_T}{p_0}\right)^2}^x
\]

- 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 $R_{AA}$

| Source       | Percentage (Description)                  |
|--------------|-------------------------------------------|
| pp reference | 9% (for $y, p_t$ integrated)              |
| MC inputs    | 5%                                        |
| Tracking     | 6%                                        |
| Trigger      | 6.4%                                      |
| Matching     | 2%                                        |
| $T_{AA}$     | 3.8% (for 0-90%)                          |
| Normalization| 2%                                        |

- **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

Embedding MC $J/\psi \rightarrow \mu\mu$
in min. bias Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV
$2.5<\gamma<4.0$, $0<p_{T}<8$ GeV/c
Effect of non-prompt $J/\psi$

Inclusive $J/\psi$ measured in ALICE

Estimate of prompt $J/\psi$ 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 $R_{AA}(B)=1$

$J/\psi$ from b-hadrons decays have a negligible influence on our measurements