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Charmonium production in p-p and Pb-Pb collisions at CERN and comparison with RHIC data

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The review of the experimental data on charmonium states production measured at the CERN SPS and in p-p and Pb-Pb collisions at LHC and comparison with the data obtained at the Brookhaven National Laboratory Relativistic Heavy Ion Collider RHIC is presented. The suppression of J/ψ production was suggested as a possible signal of quark-gluon plasma (QGP) formation in 1986 by Matsui and Satz. But the experimental and theoretical situation is more complicated. The "anomalous" suppression of J/ψ production at the CERN SPS was discovered in central Pb-Pb collisions by NA50 collaboration at 158 GeV. The effects of J/ψ suppression in cold nuclear matter and feed-down production from higher charmonium states are important in production of J/ψ at SPS energies. It was found in the PHENIX experiment at RHIC at $\sqrt{s}$ = 200 GeV that the J/ψ suppression at this energy is of the same order as the suppression at SPS for Pb-Pb. The theoretical models that could reproduce SPS Pb-Pb results at $\sqrt{s}$ = 17.3 GeV overestimate the J/ψ suppression at $\sqrt{s}$ = 200 GeV. The models with regeneration of J/ψ agree with the experimental results better. The study of charmonium production at LHC in p-p and Pb-Pb collisions also points out on the importance of regeneration process. The contribution of B-decay should be taken into account at LHC energy. Also the energy intervals between SPS, RHIC and LHC are very important for the study of the mechanism of quarkonium production and suppression, in order to investigate medium effects and conditions for quark-gluon plasma formation. If the proton and ion beams will be used at LHC with fixed targets, the measurements in the energy interval between SPS and RICH could be performed. For 7 TeV proton beam the energy will be $\sqrt{s}$= 114.6 GeV for p-Pb collisions and for 2.75 TeV lead beam $\sqrt{s}$ = 71.8 GeV for Pb-Pb collisions. It will provide a unique possibility to clarify the mechanism of J/ψ and ψ' production, particularly to separate two possibilities: i): hard production and suppression in QGP and/or hadronic dissociation or ii): hard production and secondary statistical production with $c\bar{c}$ recombination.

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1. Charmonium production at the CERN SPS

The suppression of J/ψ production by colour screening in a dense nuclear matter was suggested as one of the possible signature of quark-gluon plasma formation in relativistic heavy ions collision [1]. The charmonium production was measured in the NA50 experiment in Pb-Pb collisions at 158 GeV per nucleon [2] and in p-A collisions at 400 and 450 GeV [3]. It was observed the normal nuclear suppression of J/ψ in proton-nucleus reactions and "anomalous" suppression in central lead-lead collisions. The cross section for normal nuclear absorption in Pb-Pb collisions was obtained from p-A data by assumption of a weak energy dependence of the cross section. Then J/ψ production in p-A collisions at 400 and 158 GeV and in In-In collisions at 158 GeV per nucleon was measured in the NA60 experiment at SPS. It was found that there are rather strong energy dependence of the absorption cross section. Therefore it is very important to measure charmonium production cross section in p-p, p-A and A-A collisions in the same kinematical domain [4]. The suppression of J/ψ production in cold nuclear matter (CNM) include not only charmonium absorption in the final state, but also initial state effects. First of all it is the shadowing effect, i.e. the modification of the parton distribution function in nucleus, relative to the nucleon. Also, it is necessary to take into account the energy loss of the parton traversing the nucleus before the hard scattering. The existing shadowing parameterizations depend on the model assumptions for nuclear parton distribution. Using EKS98 shadowing parameterization [5] the extracted absorption cross section is increased. For In-In collisions at 158 GeV per nucleon the "anomalous" suppression in central collisions is rather small, while for central lead-lead collisions the value of "anomalous" suppression remains near 20 - 30 %.

2. The J/ψ production at the collider RHIC

The measurements of J/ψ production in p-p, d-Au, Au-Au and Cu-Cu collisions at $\sqrt{s}$ = 200 GeV energy were made in the PHENIX experiment at RHIC collider [6, 7]. The suppression of the J/ψ production was presented as a ratio of J/ψ production in A-A collisions to the J/ψ production in p-p collisions, normalized to the number of binary collisions, N_{coll}. This R_{AA} ratio (the nuclear modification factor), where $R_{AA} = dN_{AA}/dy/(dN_{pp}/dy* < N_{coll} >)$, was used for the comparison of the experimental data versus centrality of collisions, multiplicity, number of participants, $N_{\rm part}$, energy density, transverse momentum and so on. The suppression of the J/ψ production in Au-Au collisions in forward rapidity range $1.2 < |y| < 2.2$ was found to be stronger than suppression in rapidity range $|y| < 0.35$. For the most central events the suppression of the J/ψ production reachs a value near 80 %. There are several theoretical models which could describe experimental data with and without taking into account the regeneration of J/ψ. However the predictions for the J/ψ production at LHC energy are different – from large suppression in the model [8] to the enhancement in [9]. The J/ψ production in Au-Au collisions at large transverse momentum $p_{\rm T}$>5 GeV/c for mid-rapidity range was also measured in STAR experiment at RHIC. The suppression for the J/ψ production is smaller than measured at PHENIX and is near 50 % for the most central collisions [10]. For extractions of the CNM effect, the PHENIX data for Au-Au and d-Au collisions were analyzed simultaneously. It is suggested that in p-p, p-A and d-Au collisions the hot and dense nuclear matter is not formed and the normal suppression of charmonium production is produced only by cold nuclear matter. The nuclear modification factor for cold nuclear matter

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$R_{AA}(CNM)$ in Au-Au collisions was obtained. The ratio $R_{AA}/R_{AA}(CNM)$ shows the "anomalous" suppression of the J/ψ production in the hot and dense nuclear matter produced in relativistic heavy ions collisions. At $\sqrt{s}$ = 200 GeV the $R_{AA}/R_{AA}(CNM)$ ratio is approximately equal for different ranges of rapidity [11]. From the dependence of NA50, NA60 and PHENIX data on multiplicity it is seen that at RHIC energy "anomalous" suppression of J/ψ for all colliding nuclei is the same as at SPS energy. However the suppression in PHENIX is stronger than suppression in Pb-Pb collisions at SPS by using the dependence of "anomalous" J/ψ suppression on N_{part} (fig1). So it is important to choose the correct parameter for comparison the data.

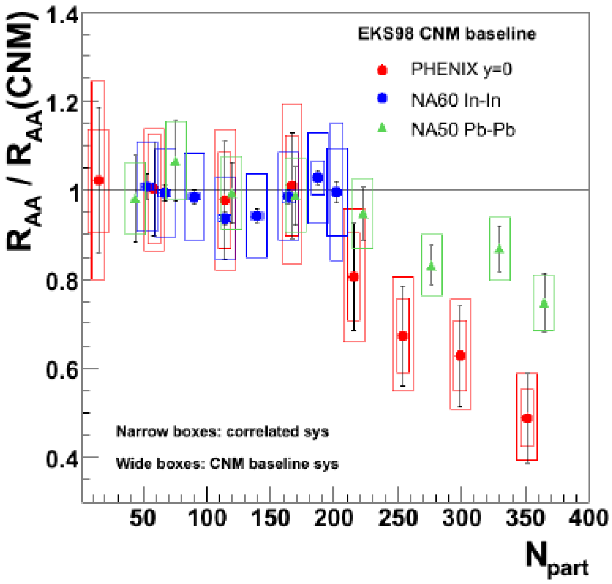

Figure 1: The comparison of NA50, NA60 and PHENIX R_{AA} results versus N_{part}.

3. Quarkonium production at the LHC

The LHC collider at CERN now gives the possibility to measure quarkonium production at the new energy range more than ten times higher than at RHIC. In experiments ALICE [12], ATLAS [13], CMS [14] and LHCb [15] at LHC, the charmonium production was measured in different rapidity and transverse momentum ranges. The J/ψ production during years 2010-2012 was measured in p-p collisions at 2.76 TeV, 7 TeV and 8 TeV and in Pb-Pb collisions at 2.76 TeV. It is planned to measure p-Pb collisions for detailed investigation of the cold nuclear matter effects.

3.1 Charmonium production in p-p collisions

Measurement of the J/ψ production in p-p collision at the same energy as in Pb-Pb collision, provides the baseline for extracting the nuclear modification factor R_{AA}. The mechanism of J/ψ production is investigated and the contribution of B- decay to J/ψ production is measured. There is a good agreement for p-p collision between the data obtained in ALICE, LHCb, CMS and ATLAS experiments in the same kinematical domains [16]. The J/ψ production cross section depends on rapidity. For forward rapidity the cross section is smaller. By increasing the energy the mean transverse momentum and production cross section of J/ψ becomes larger. The contribution of B-decay to J/ψ production cross section depends on rapidity and increases for larger J/ψ transverse momentum. This contribution is approximately 10 % for $p_{\rm T}$ near 1.5 GeV/c [17].

3.2 Charmonium production in Pb-Pb collisions

Charmonium production in Pb-Pb collisions at 2.76 TeV was measured at LHC in ALICE, CMS and ATLAS experiments. In ALICE experiment the transverse momentum of inclusive J/ψ mesons was measured from values near zero up to 8 GeV/c in rapidity range $|y| < 0.9$ (for J/ψ decay into two electrons) and $2.5 < y < 4$ (for muon channel). In ATLAS and CMS experiments charmonium production was measured in the rapidity range $|y| < 2.4$, but the range of transverse momentum values depended on rapidity. In ATLAS experiment only J/ψ mesons with large transverse momentum $p_{\rm T} > 6.5$ GeV/c were measured. The comparison of PHENIX and ALICE R_{AA} results is shown in the fig.2 [16, 7].

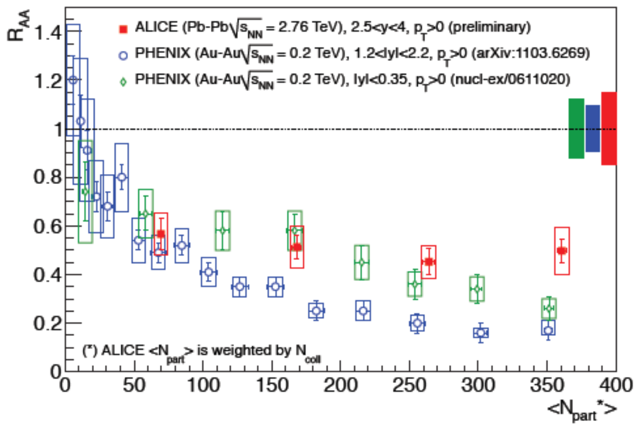

Figure 2: The comparison of PHENIX and ALICE R_{AA} results

The R_{AA} dependence on centrality in ALICE experiment is not so strong, as in PHENIX. In ALICE for the most central events and $2.5 < y < 4$ range the R_{AA} value is two times larger than measured in PHENIX, so the suppression of J/ψ production is smaller. But in CMS experiment [17] the suppression of "prompt" J/ψ production (directly produced and obtained from feed-down decay) for the most central event is approximately equal to the suppression measured at RHIC. A comparison of the R_{AA} centrality dependence, measured in ALICE, was done with a statistical hadronization model calculation, which is in good agreement with the RHIC data. The model predicts the larger values for R_{AA} at LHC than at RHIC in agreement with ALICE experimental data [19]. The importance of J/ψ regeneration process is also seen from LHC experimental data.

4. Quarkonium production at the ALICE dimuon spectrometer

In order to understand the problem of quarkonium suppression it is necessary to measure p-p, p-A and Pb-Pb collisions in the same kinematical domains. The energy intervals between AGS, SPS, RHIC and LHC are very important to study the mechanism of quarkonium production and suppression, in order to investigate medium effects and conditions of quark-gluon plasma formation. However the luminosity in collider experiments at RHIC is decreased for low energy. If the proton and ion beams would be used at LHC with fixed targets, the energy interval between SPS and RHIC in p-A and A-A collisions could be covered. For 7 TeV proton beam, the energy in N-N c.m. is $\sqrt{s}$ = 114.6 GeV, for Pb beam at 2.75 TeV it is $\sqrt{s}$ = 71.8 GeV. This is a unique possibility to clarify the mechanism of charmonium, J/ψ and ψ' production, to separate two possibilities: i): hard production and suppression in QGP and/or hadronic dissociation or ii): hard production and secondary statistical production with recombination, since the probability of recombination decreases with decreasing energy of collision in thermal model [20]. In order to study the feasibility of using the fixed target at LHC for charmonium production, the geometrical acceptances for J/ψ production on fixed target by means of AliRoot - FAST simulations are obtained. Then they are compared with acceptances at collider experiments (RHIC and LHC) and with fixed target experiments at SPS and HERA for J/ψ production. The counting rates are calculated and it is shown that the J/ψ production on fixed targets at LHC could be measured with high statistics collected in several days of data taking [21]. As described in [21] for quarkonium production the phenomenological Colour Evaporation Model (CEM) is used. The rapidity and transverse momentum distributions for "prompt" J/ψ production are obtained respectively as a parameterization of the CEM predictions and by extrapolating to LHC energy the J/ψ transverse momentum $p_{\rm T}$ distribution, measured at mid-rapidity by the CDF experiment at c.m. energy near 1.8 TeV. The 30000 J/ψ events are generated and geometrical acceptances of the ALICE dimuon spectrometer are obtained for J/ψ, produced in Pb-Pb collisions at $\sqrt{s}$ = 5.5 TeV in N-N c.m. system and in p-p collisions at $\sqrt{s}$ = 14 TeV in agreement with the existing calculations [23]. In the same frame the geometrical acceptances of J/ψ production for PHENIX at RHIC and fixed target experiments NA50 at SPS and HERA-B are calculated for comparison.

4.1 Geometrical acceptance for J/ψ production on fixed target for ALICE dimuon spectrometer

Geometrical acceptances are obtained for fixed target Pb-Pb collisions at the energy 2.75 TeV per nucleon, ($\sqrt{s}$ = 71.8 GeV in N-N c.m.) for J/ψ production at point z = 0 and outside of the ITS detector at point z=+50 cm in the direction to the dimuon spectrometer. The transverse momentum distribution for J/ψ are generated using $p_{\rm T}$ spectra in the CDF form, the same as for HERA and PHENIX, consistent with CEM model. The parameters of distribution are energy scaled: $dN/d{\rm p_T}$= c $p_{\rm T}$[1+ (35 $\pi {\rm p_T}$/ 256 $\langle p_{\rm T}\rangle)^2]^{-6}$, where $\langle p_{\rm T}\rangle$ = 1.4. For rapidity distribution the Gaussian spectra is used with the mean values equal to y_{cm} = 0 and σ = 1.1. J/ψ are accepted in the rapidity range -2.5< y <- 4.0 (- 2.97< y <- 4.09) for J/ψ production at the point z = 0 (z=+50 cm). The results are shown in the fig.3. The geometrical acceptances, I, are equal to 12.0 % for J/ψ production at z=0 point and 7.97 % at z=+50 cm.

The J/ψ production in p-p and p-A collisions at LHC energy 7 TeV ($\sqrt{s}$ = 114.6 GeV in N-N c.m.) is calculated by using $p_{\rm T}$ spectra in the same form as for Pb-Pb collision, but with the energy scaled parameter $\langle p_{\rm T}\rangle$ = 1.6. For rapidity distribution the Gaussian spectra is used with the mean values equal to y_{cm} = 0 and σ = 1.25. The geometrical acceptances for J/ψ without transverse momentum cut on single muon and with transverse momentum cut $p_{\rm T}>$ 1 GeV/c are calculated.

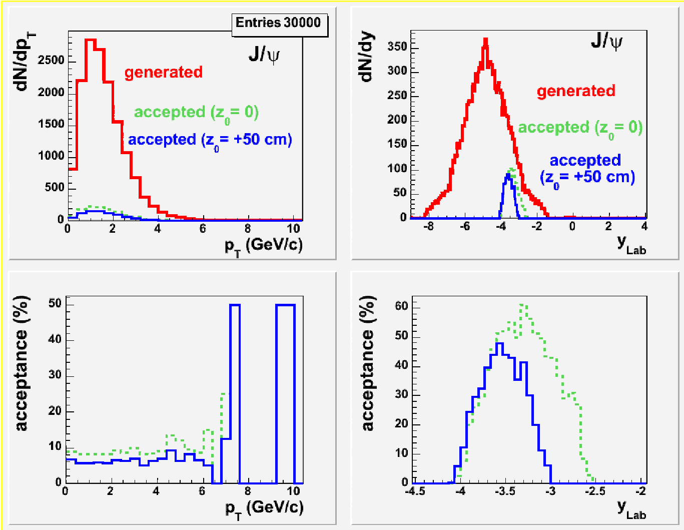

Figure 3: The transverse momentum and rapidity distributions for J/ψ events, produced at z=+50 cm (solid lines) and z=0 (dashed lines) in fixed target Pb-Pb collisions at $\sqrt{s}$ = 71.8 GeV (top) and corresponding acceptances (bottom).

The results are shown in the Table 1. The calculated geometrical acceptances for fixed target measurement are of the same order and even larger than geometrical acceptances for colliding nuclei in ALICE.

Table 1: Geometrical acceptances (in persent) for p-A collisions at a fixed target.

z (cm)	η range	$\sqrt{s}$ =0.078 TeV		$\sqrt{s}$ =0.1146 TeV	
		all p_T	$p_T>$ 1 GeV/c	all p_T	$p_T>$ 1 GeV/c
0	-4.00 $\leftrightarrow$-2.50	12.0	9.79	8.54	6.77
-50	-3.76 $\leftrightarrow$-2.50	7.44	6.20	5.07	4.11
+50	-4.09 $\leftrightarrow$-2.97	7.97	6.62	5.98	4.89

4.2 Luminosity, cross sections and counting rates for p-p, p-A and Pb-Pb collisions

As it was already used for the experiment on collider with a fixed target at HERA-B [24], the target in the form of thin ribbon could be placed around the main orbit of LHC. The life time of the beam is determined by the beam-beam and beam-gas interactions. Therefore after some time the particles will leave the main orbit and interact with the target ribbon. So for fixed target measurements only halo of the beam will be used. Therefore no deterioration of the main beam will be introduced. The experiments at different interaction points will not feel any presence of the fixed target at the IP of ALICE. The luminosity estimate is shown in the Table 2. It is calculated for 1.15$\cdot$ 10^{11} protons per bunch, 44 bunches and life time 15.4 hours. From these parameters we get particle loss of $3.2 \cdot 10^{12}$ during one hour and luminosity about $1.5 \cdot 10^{29}$ for 500 micron lead ribbon. Since the target ribbon should not interfere during the beam formation and acceleration process it should be lifted in the working position after the tuning of the beam. The value of the nucleon-nucleon charmonium total production cross section shown in the Table 2 for 14 TeV was calculated by CEM model with MRST HO PDF. The cross sections for lower energies were obtained by interpolation of the measured at RHIC proton-proton collision at $\sqrt{s}$ = 200 GeV, from NA51 p-p and p-d experiment at 450 GeV per nucleon ($\sqrt{s}$ = 29.1 GeV) and extracted from the data of NA50 experiment at $\sqrt{s}$ = 27.4 GeV for proton-lead collisions.

Table 2: Luminosity, cross sections ($x_F > 0$) and counting rates.

System	$\sqrt{s}$, TeV	σ_{nn}, μb	σ_{pA}, μb ($A^{0.92}\sigma_{nn}$)	I,%	IBσ_{pA}, μb	L, $cm^{-2}s^{-1}$	Rate, h^{-1}
pp	14	32.9	32.9	4.7	0.091	$5 \cdot 10^{30}$	1635
pp_{RHIC}	0.200	2.7	2.7	3.59	0.0057	$2 \cdot 10^{31}$	410
pPb_{NA50}	0.0274	0.19	25.7	14.0	0.212	$7 \cdot 10^{29}$	535
pPb_{fixed}	0.1146	0.65	80.2	5.98	0.310	$1 \cdot 10^{29}$ (*)	112
pPb_{fixed}	0.0718	0.55	74.6	7.97	0.349	$1 \cdot 10^{29}$	126
$PbPb_{fixed}$	0.0718	0.55	11970	7.97	42.9	$2.2 \cdot 10^{27}$ (**)	378

(*) - pPb_{fixed}, 500 μ wire, $3.2 \cdot 10^{12}$ protons/60 min.
(**) - $PbPb_{fixed}$, 500 μ wire, $6.8 \cdot 10^{9}$ ions/60 min.

With the counting rate values presented in Table 2 for p-A and A-A collisions with fixed target high statistical results could be obtained for possible measurements of J/ψ production. For A-A collisions luminosity is smaller but the production cross section is larger. Therefore the counting rate is of the same order. It is also clear that the measurement of ψ' production is feasible with better statistical accuracy than at RHIC collider.

In conclusion, the capabilities of the ALICE dimuon spectrometer to measure the charmonium production in the proton-lead and lead-lead collisions with fixed target have been investigated with AliRoot-FAST simulations. The evaluation of geometrical acceptances and counting rates is made. The use of fixed target at LHC could provide in a short time the data in a new range of energy between SPS and RHIC for different targets and maybe for different projectile nuclei with high statistics. Therefore the important information about mechanism of charmonium production and possible QGP formation could be obtained.

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