

Observation of χ_c and χ_b nuclear suppression via dilepton polarization measurements

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(Dated: February 25, 2013)

We demonstrate that it is possible to use the polarization of vector quarkonia, measured from dilepton event samples, as an instrument to study the suppression of χ_c and χ_b in heavy-ion collisions, where a direct determination of signal yields involving the identification of low-energy photons is essentially impossible. A change of the observed J/ψ and $\Upsilon(1S)$ polarizations from proton-proton to central nucleus-nucleus collisions would directly reflect differences in the nuclear dissociation patterns of S and P states and may provide a strong indication for quarkonium sequential suppression in the quark-gluon plasma.

PACS numbers: 12.38.Mh, 13.20.Gd, 25.75.Nq, 11.80.Cr

I. INTRODUCTION

Hypotheses on the suppression of χ_c and χ_b production in nucleus-nucleus collisions play a crucial role in the interpretation of the J/ψ and $\Upsilon(1S)$ measurements from SPS [1], RHIC [2] and LHC [3] in terms of evidence of quark-gluon plasma (QGP) formation. The observation of the χ_c and χ_b suppression patterns in Pb-Pb collisions at the LHC could confirm or falsify the “sequential quarkonium melting” scenario [4, 5] and, therefore, discriminate between the QGP interpretation and other options. However, a direct observation of the χ_c and χ_b signals in their radiative decays to J/ψ and $\Upsilon(1S)$ is practically impossible in heavy-ion collisions, given the very large number of background photons produced in such events.

In this paper we show that this important missing piece of information can be obtained by measuring how the dilepton decay distributions of prompt J/ψ and $\Upsilon(1S)$ change from proton-proton (or peripheral nucleus-nucleus) to central nucleus-nucleus collisions, bypassing the difficulty of explicitly identifying the events containing χ_c and χ_b decays.

The demonstration of the result is made by steps. In Sec. II we describe how the polarization is transferred in the decays to lighter quarkonium states and summarize the present knowledge of the feed-down contributions in collider experiments. In Sec. III we consider two illustrative polarization scenarios, complementing the existing experimental information on prompt- J/ψ and $\Upsilon(1S)$ polarizations with educated guesses about the still unknown polarizations of the P -states. In Sec. IV we formalize the relations between the P -to- S -state feed-down fractions and the observable polarizations of directly and indirectly produced states. Using these ingredients, in Sec. V we illustrate the main result of the paper, discussing the feasibility of the χ suppression measurement using dilepton angular distributions at the LHC.

The notations used in this paper for angles and polarization parameters are those defined in Ref. [6]. We report here for convenience the most general form of the

observable angular distribution of J/ψ and Υ decays into lepton pairs:

$$W(\cos\vartheta, \varphi) \propto \frac{1}{(3 + \lambda_\vartheta)} (1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi), \quad (1)$$

where ϑ and φ are the polar and azimuthal emission angles of one of the leptons with respect to a system of axes defined in the dilepton rest frame and $\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}$ are the anisotropy parameters.

II. POLARIZATION CONTRIBUTIONS FROM FEED-DOWN DECAYS

Many of the prompt J/ψ and Υ mesons produced in hadronic collisions result from the decay of heavier S - or P -wave quarkonia. However, the existing polarization measurements at collider energies make no distinction between directly and indirectly produced states. The role of the feed-down from heavier S states (responsible, for example, for about 8% of J/ψ production at low p_T [7]) is rather well understood. Data of the BES [8] and CLEO [9] experiments in e^+e^- collisions indicate that in the decays $\psi' \rightarrow J/\psi\pi\pi$ and $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi$ the dipion system is produced predominantly in the spatially isotropic (S -wave) configuration, meaning that no angular momentum is transferred to it. Consequently, the angular momentum alignment is preserved in the transition from the $2S$ to the $1S$ state. This allows us to assume that the dilepton decay angular distribution of the J/ψ [$\Upsilon(1S)$] mesons resulting from ψ' [$\Upsilon(2/3S)$] decays is the same as the one of the ψ' [$\Upsilon(2/3S)$], provided that a common polarization axis is chosen for the two particles. At high momentum, when the J/ψ and ψ' directions with respect to the centre of mass of the colliding hadrons practically coincide, ψ' mesons and J/ψ mesons from ψ' decays have the same observable polarization with respect to any system of axes defined on the basis of the directions of the colliding hadrons. In the case of the polar anisotropy parameter λ_ϑ , for instance, the

J_z	$\lambda_\vartheta(S)$	$\lambda_\vartheta(P_1)$	$\lambda_\vartheta(P_2)$
0	-1	+1	-3/5
± 1	+1	-1/3	-1/3
± 2	-	-	+1

TABLE I. Values of the observable polar anisotropy parameter λ_ϑ of the J/ψ [$\Upsilon(1S)$] dilepton decay distribution, corresponding to pure angular momentum states (J_z) of the *directly* produced particle (J/ψ [$\Upsilon(1S)$] itself, χ_1 or χ_2). The results are obtained in the high-momentum approximation (for $p > 5$ GeV/ c they are affected by an error smaller than 1%) and are valid not only in the E1 approximation (usually assumed in the literature), but also including all orders of the photon radiation expansion [10].

relative error, $|\Delta\lambda_\vartheta/\lambda_\vartheta|$, induced by the approximation of considering the J/ψ and ψ' directions as coinciding is $\mathcal{O}[(\Delta m/p)^2]$, where Δm is the $2S - 1S$ mass difference and p the total laboratory momentum of the dilepton. For $p > 5$ GeV/ c this error is of order 1%. Moreover, the directly produced J/ψ [$\Upsilon(1S)$] and ψ' [$\Upsilon(2/3S)$] are expected to have the same production mechanisms and, therefore, very similar polarizations. As a consequence, the polarization of J/ψ [$\Upsilon(1S)$] from ψ' [$\Upsilon(2/3S)$] can be considered to be almost equal to the polarization of directly produced J/ψ [$\Upsilon(1S)$], so that, at least in first approximation, the two contributions can be treated as one.

On the contrary, the J/ψ [$\Upsilon(1S)$] mesons resulting from χ_{cJ} [χ_{bJ}] radiative decays can have very different polarizations with respect to the directly produced ones. Directly produced P and S states can originate from different partonic and long-distance processes, given their different angular momentum and parity properties. Moreover, the emission of the spin-1 and always transversely polarized photon necessarily changes the angular momentum projection of the $q\bar{q}$ system in the $P \rightarrow S$ radiative transition. As a result, the relation between the “spin-alignment” of the directly produced P or S state and the shape of the observed dilepton angular distribution is totally different in the two cases: for example, if directly produced χ_{c1} and J/ψ both had “longitudinal” polarization (angular momentum projection $J_z = 0$ along a given quantization axis), the shape of the dilepton distribution would be of the kind $\propto 1 - \cos^2\vartheta$ for the direct J/ψ and $\propto 1 + \cos^2\vartheta$ for the J/ψ from χ_{c1} . Table I lists values of the observable polar anisotropy parameter λ_ϑ of the J/ψ [$\Upsilon(1S)$] dilepton decay distribution, corresponding to pure angular momentum states of the *directly* produced particle. In particular, while for directly produced S states $-1 < \lambda_\vartheta < +1$, for those from decays of P_1 and P_2 states the lower bound is $-1/3$ and $-3/5$, respectively. More detailed constraints on the three anisotropy parameters λ_ϑ , λ_φ and $\lambda_{\varphi\varphi}$ in the cases of directly produced S state and S states from decays of P_1 and P_2 states can be found in Ref. [10]. Figure 3 of that work shows that the allowed parameter space of the decay anisotropy pa-

rameters for the directly produced J/ψ [$\Upsilon(1S)$] strictly includes the one of the S -states from P_2 decays, which, in turn, strictly includes the one of the S -states from P_1 decays.

The feed-down fractions are not well-known experimentally. In the charmonium case, the χ_c -to- J/ψ and χ_{c2} -to- χ_{c1} yield ratios have been measured by CDF [11] in the rapidity interval $|y| < 0.6$, with insufficient precision to indicate or exclude important p_T dependencies. The p_T -averaged results,

$$\begin{aligned} R(\chi_{c1}) + R(\chi_{c2}) &= 0.30 \pm 0.06, \\ R(\chi_{c2})/R(\chi_{c1}) &= 0.40 \pm 0.02, \end{aligned} \quad (2)$$

where $R(\chi_{c1})$ and $R(\chi_{c2})$ are the fractions of prompt J/ψ yield due to the radiative decays of χ_{c1} and χ_{c2} , effectively correspond to a phase-space region (low p_T and central rapidity), much smaller than the one covered by the LHC experiments.

CDF also measured [12] the fractions of $\Upsilon(1S)$ mesons coming from radiative decays of $1P$ and $2P$ states as, respectively, $R(\chi_{b1}) + R(\chi_{b2}) = (27 \pm 8)\%$ and $R(\chi'_{b1}) + R(\chi'_{b2}) = (11 \pm 5)\%$, for $p_T > 8$ GeV/ c and without discrimination between the $J = 1$ and $J = 2$ states. These results tend to indicate that the contribution of the feed-down from P states to $\Upsilon(1S)$ production is at least as large as in the corresponding charmonium case, even if the experimental error is quite large. The same indication is provided with higher significance by the Υ polarization measurement of E866 [13], at low p_T , as discussed in the next section.

III. TWO EXAMPLE SCENARIOS

In this section we derive, using available experimental and theoretical information, two illustrative scenarios for the polarizations of the charmonium and bottomonium families. In our considerations we will use the following addition rule [14]:

$$\vec{\lambda}^{\text{prt}} = \frac{\frac{[1-R(P_1)-R(P_2)]\vec{\lambda}^{\text{dir}}}{3+\lambda_\vartheta^{\text{dir}}} + \frac{R(P_1)\vec{\lambda}^{P_1}}{3+\lambda_\vartheta^{P_1}} + \frac{R(P_2)\vec{\lambda}^{P_2}}{3+\lambda_\vartheta^{P_2}}}{\frac{[1-R(P_1)-R(P_2)]}{3+\lambda_\vartheta^{\text{dir}}} + \frac{R(P_1)}{3+\lambda_\vartheta^{P_1}} + \frac{R(P_2)}{3+\lambda_\vartheta^{P_2}}}, \quad (3)$$

where $\vec{\lambda}^{\text{prt}}$ are the observable polarization parameters of the promptly produced S state, being $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\varphi\varphi})$, $\vec{\lambda}^{\text{dir}}$ are the polarization parameters of the directly produced S state, $R(P_1)$ and $R(P_2)$ the fractions of events produced by the decays of P_1 and P_2 states and $\vec{\lambda}^{P_1}$ and $\vec{\lambda}^{P_2}$ the corresponding polarizations.

Figure 1 illustrates how the CDF measurement of prompt- J/ψ polarization [15] can be translated in a range of possible values of the direct- J/ψ polarization, using Eq. 3, the available information about the feed-down fractions and all possible combinations of hypotheses of pure polarization states for χ_{c1} and χ_{c2} . The feed-down fraction is set to 0.42, two standard deviations

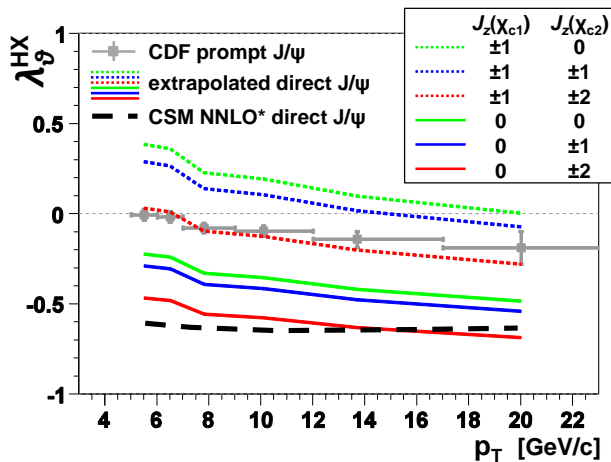


FIG. 1. Direct- J/ψ polarizations (λ_θ) extrapolated from the CDF measurement of prompt- J/ψ polarization (in the helicity frame), using several scenarios for the χ_c polarizations. The order of the lines from top to bottom is the same as in the legend. The NNLO* prediction of direct- J/ψ polarization including only colour-singlet contributions [16] is also shown.

higher than the central CDF value (Eq. 2); using 0.30 simply decreases the spread between the curves. The $R(\chi_{c2})/R(\chi_{c1})$ ratio is set to 0.40; changes remaining compatible with the CDF measurement give almost identical curves.

In the scenario in which χ_{c1} and χ_{c2} are produced with, respectively, $J_z = 0$ and $J_z = \pm 2$ polarizations the CDF measurement is seen to be described by partial next-to-next-to-leading order Colour Singlet Model predictions (NNLO* CSM) for directly produced S -states quarkonia [16]. This is the J/ψ polarization scenario that we will adopt in following considerations. Its validity can be probed by experiments able to discriminate if the J/ψ is produced together with a photon such that the two are compatible with being χ_{c1} or χ_{c2} decay products. Such dilepton events, resulting from χ_c decays, should show a full transverse polarization ($\lambda_\theta^{\chi_{c1}} = \lambda_\theta^{\chi_{c2}} = +1$), while the directly produced J/ψ mesons should have a strong longitudinal polarization ($\lambda_\theta^{\text{dir}} \simeq -0.6$).

We will not discuss here a possible scenario based on non-relativistic QCD (NRQCD) calculations, which include non-perturbative contributions and, in particular, colour-octet processes. In fact, the large transverse polarization predicted by current calculations for the directly produced S -states [17] could be reconciled with the prompt CDF data only assuming a huge deviation from the measured feed-down from χ_c [$R(\chi_c) \simeq 70\%$] and, at the same time, the maximum possible longitudinal polarization for the J/ψ from χ_c (this latter assumption would be in contradiction with the corresponding prediction of NRQCD itself).

We will base our second scenario, for the bottomonium family, on the precise and detailed measurement of E866 [13], shown in Fig. 2a. This result offers several

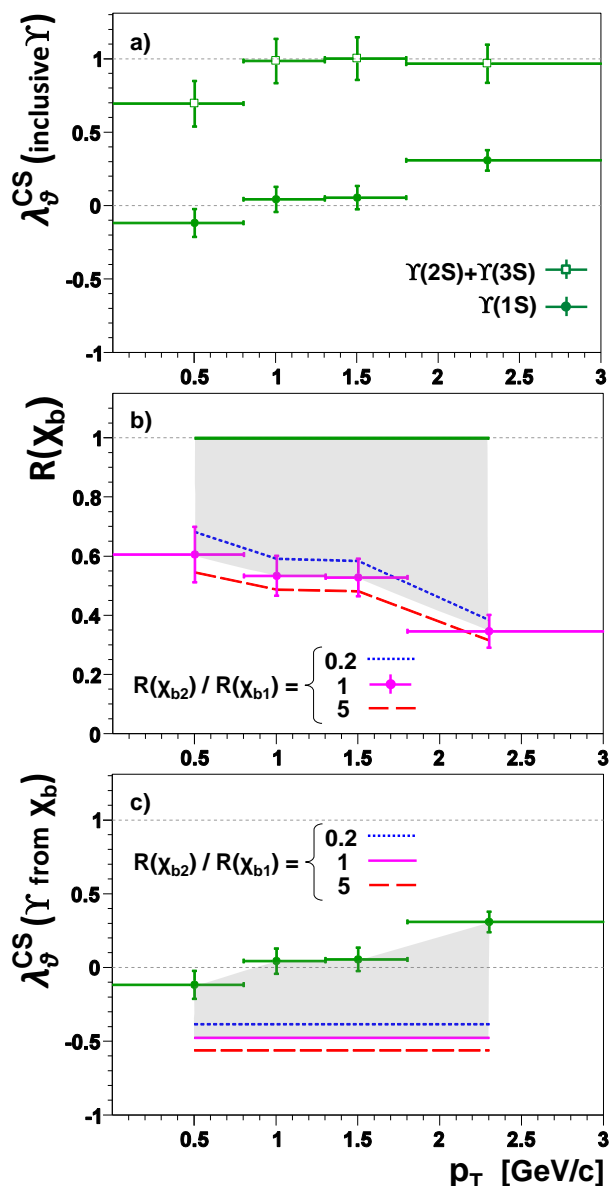


FIG. 2. The E866 measurement of $\Upsilon(1S)$ and $\Upsilon(2S)+\Upsilon(3S)$ polarizations (in the Collins-Soper frame [19]) as a function of p_T (a), the deduced ranges for the fraction of $\Upsilon(1S)$ mesons coming from χ_b decays (b) and the deduced range of their possible polarizations (c). An additional systematic uncertainty of ± 0.06 is not included in the error bars of the λ_θ data points in (a). The error bars in the derived lower limit of the range for $R(\chi_b)$ (b) reflect the uncertainty in the λ_θ measurements, assuming that the global systematic uncertainty affects the $\Upsilon(1S)$ and $\Upsilon(2S)+\Upsilon(3S)$ measurements in a fully correlated way. The lower limits for $R(\chi_b)$ and $\lambda_\theta(\Upsilon \text{ from } \chi_b)$ depend on the ratio $R(\chi_{b2})/R(\chi_{b1})$, for which three different values are assumed.

interesting cues. It is remarkable that the $\Upsilon(2S)$ and $\Upsilon(3S)$ are found to be almost fully polarized, while the $\Upsilon(1S)$ is only weakly polarized. The most reasonable explanation of this fact is that the fraction of $\Upsilon(1S)$ mesons

coming from χ_b decays is large and its polarization is very different with respect to the polarization of the directly produced $\Upsilon(1S)$. In fact, in the assumption that all directly produced S states have the same polarization, we can translate the E866 measurement into a lower limit for the feed-down fraction $R(\chi_b)$ from P states, summing together $1P_1$, $1P_2$, $2P_1$, $2P_2$ contributions. We use Eq. 3 and the values in Table I (the average longitudinal momentum of the $\Upsilon(1S)$ in the E866 data is ~ 4.5 GeV/ c) assuming that the $\Upsilon(2S) + \Upsilon(3S)$ result has a negligible contamination from $\chi'_b \rightarrow \Upsilon(2S)\gamma$ decays and, therefore, provides a good evaluation of the polarization of the directly produced S states (a conservative assumption for this specific calculation). The lower limit for $R(\chi_b)$ corresponds to the case $J_z(\chi_{b1}) = J_z(\chi'_{b1}) = \pm 1$, $J_z(\chi_{b2}) = J_z(\chi'_{b2}) = 0$, in which the $\Upsilon(1S)$ mesons from χ_b decays have the largest negative value of λ_ϑ . The result, depending slightly on the assumed ratio between P_2 and P_1 feed-down contributions, is shown in Fig. 2b as a function of p_T . More than 50% of the $\Upsilon(1S)$ are produced from P states for $\langle p_T \rangle \simeq 0.5$ GeV/ c , and more than 30% for $\langle p_T \rangle \simeq 2.3$ GeV/ c . These limits are appreciably higher than the value of the feed-down fraction of J/ψ from χ_c measured at similar energy, low p_T and mid rapidity [18]. We remind that we have obtained only a lower limit (no upper limit is implied by the data), corresponding to the case in which χ_{b1} and χ_{b2} are always produced in the same very specific and pure angular momentum configurations. Any deviation from this extreme case would lead to higher values of the indirectly determined feed-down fraction.

The E866 measurement data also set an upper limit on the combined polarization of χ_{b1} and χ_{b2} . Figure 2c shows the derived range of possible polarizations of $\Upsilon(1S)$ coming from χ_b . The upper bound, corresponding to $R(\chi_b) = 1$, coincides with the measured $\Upsilon(1S)$ polarization. The lower bound, slightly depending on the relative contribution of χ_{b1} and χ_{b2} , is not influenced by the E866 data and corresponds to the minimum (p_T dependent) value of $R(\chi_b)$ represented in Fig. 2b. The second strong indication of the E866 data is, therefore, that at low p_T the $\Upsilon(1S)$ coming from χ_b decays has a longitudinal component in the Collins-Soper frame larger than $\sim 30\%$ ($\lambda_\vartheta \gtrsim 0.1$), being $\sim 60\%$ ($\lambda_\vartheta \sim -0.5$) the maximum amount of longitudinal polarization that the $\Upsilon(1S)$ produced in this way is allowed to have.

Also CDF has measured [20], at higher p_T , an almost unpolarized production of the $\Upsilon(1S)$ mesons. However, the precision of the $\Upsilon(2S)$ and $\Upsilon(3S)$ data does not allow us to draw any conclusion about the difference between the polarizations of directly and indirectly produced states and, therefore, to infer a possible scenario of polarizations for the $\Upsilon(1S)$ coming from χ_b decays. A comparison with the theory predictions for the directly produced $\Upsilon(1S)$ [16, 17] would lead to conjectures identical to those made in the J/ψ case, and, therefore, to a bottomonium polarization scenario completely analogous to the charmonium scenario described above.

IV. BASIC PROCEDURES AND TOOLS

The E866 example suggests an alternative method to determine the polarization of the P -states, particularly suitable to certain experimental conditions and always useful as a cross-check of direct determinations. In fact, referring again to the scenario of Fig. 2, a measurement of $R(\chi_b)$ would transform the upper bound on the polarization of $\Upsilon(1S)$ from χ_b decays into a univocal determination. We can formulate a general way of measuring the combined polarization of P_1 and P_2 states, consisting in the following set of measurements: 1) polarization, $\bar{\lambda}^{1S}$, of the inclusively produced prompt- $1S$ state; 2) polarization, $\bar{\lambda}^{2S}$, of the $2S$ and/or $3S$ states, assumed to be mostly directly produced; 3) fraction, $R(P)$, of $1S$ states produced in the decays of P states. The polarization of the $1S$ states coming from P states can then be determined as using the expression

$$\bar{\lambda}^P = \frac{(3 + \lambda_\vartheta^{2S})\bar{\lambda}^{1S} - [1 - R(P)](3 + \lambda_\vartheta^{1S})\bar{\lambda}^{2S}}{R(P)(3 + \lambda_\vartheta^{1S}) + \lambda_\vartheta^{2S} - \lambda_\vartheta^{1S}}, \quad (4)$$

obviously defined only for $R(P) > 0$ ($\bar{\lambda}^{2S} - \bar{\lambda}^{1S} \rightarrow 0$ for $R(P) \rightarrow 0$). As discussed in Ref. [10], $\bar{\lambda}^{P_1}$ and $\bar{\lambda}^{P_2}$, anisotropy parameters of the dilepton decay distribution of the daughter $1S$ state, reflect univocally the average angular momentum configurations in which the P_1 and P_2 states are produced. A measurement of $\bar{\lambda}^P$, merging P_1 and P_2 polarizations, can give significant indications, especially if its value is close to the boundaries of the parameter space and, therefore, does not suffer cancellation effects (as the E866 example suggests). This method is convenient if the event sample becomes too small after the requirement of a photon coming from the $P \rightarrow S$ transition, precluding a detailed angular analysis.

For our main result, presented in the next section, we will make use of the inverse procedure, in which a determination of $R(P)$ is obtained by performing dilepton polarization measurements. For example, from measurements of λ_ϑ^{1S} , λ_ϑ^{2S} and λ_ϑ^P the χ feed-down is determined as

$$R(P) = \frac{(3 + \lambda_\vartheta^P)(\lambda_\vartheta^{2S} - \lambda_\vartheta^{1S})}{(3 + \lambda_\vartheta^{1S})(\lambda_\vartheta^{2S} - \lambda_\vartheta^P)}. \quad (5)$$

The significance of this indirect determination will, in general, depend on the choice of the polarization frame and will be higher in a frame where the differences between the three λ_ϑ parameters are more significant. An analysis considering also the azimuthal anisotropy parameters λ_φ and $\lambda_{\vartheta\varphi}$ (formulas similar to Eq. 5, but depending also on these two parameters, can be easily deduced from Eq. 3) would lead to the maximum significance independently of the reference frame. A simpler alternative to achieve the same result is to use the frame-independent parameter $\mathcal{F} = (1 + \lambda_\vartheta + 2\lambda_\varphi)/(3 + \lambda_\vartheta)$ introduced in Ref. [14]:

$$R(P) = \frac{\mathcal{F}^{2S} - \mathcal{F}^{1S}}{\mathcal{F}^{2S} - \mathcal{F}^P}. \quad (6)$$

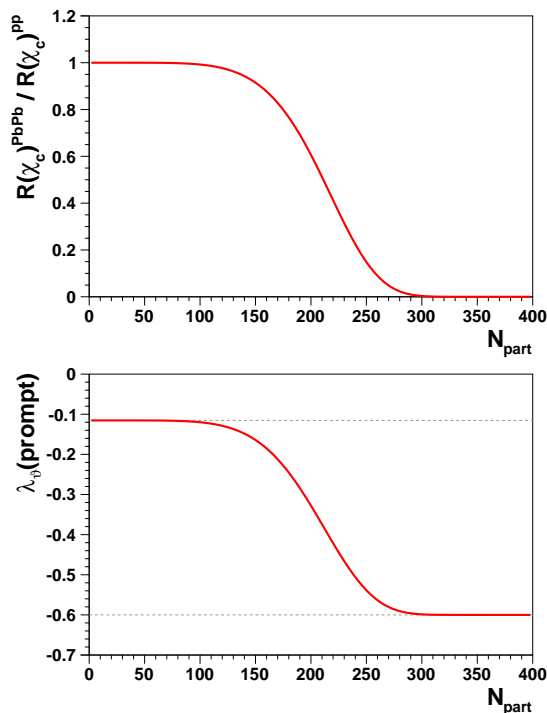


FIG. 3. A hypothetical variation of $R(\chi_c)$ (normalized to the pp value) with the centrality of the Pb-Pb collision (top) and the consequent variation of the polarization parameter λ_θ of the prompt- J/ψ decay distribution (bottom), according to the charmonium polarization scenario discussed in the text.

V. NUCLEAR DISSOCIATION OF P STATES

The possibility of determining the feed-down fraction from P states purely on the basis of *dilepton* properties is particularly valuable in the perspective of quarkonium measurements in heavy-ion collisions, where a direct determination of the χ yields is essentially impossible.

Figure 3 illustrates the concept of the method. The top panel shows an hypothetical $R(\chi_c)$ pattern inspired from the sequential charmonium suppression scenario, in which the χ_c yield disappears rapidly beyond a critical value of the number of nucleons participating in the interaction (N_{part}). This effect would be reflected by a change in the observed prompt- J/ψ polarization. As shown in the bottom panel, according to the scenario presented in Sec. III the polarization should become significantly more longitudinal (in the helicity frame) after the disappearance of the transversely polarized feed-down contribution due to χ_c decays. We are assuming that the “base” polarizations of the directly produced S and P states remain essentially unaffected by the nuclear medium and are, therefore, not distinguishable from those measurable in pp collisions.

In general, the determination of $R(\chi_c)$ as a function of number of participants from the corresponding polarization measurements requires the knowledge of the polarization of the J/ψ coming from χ_c decays (Eq. 5). This

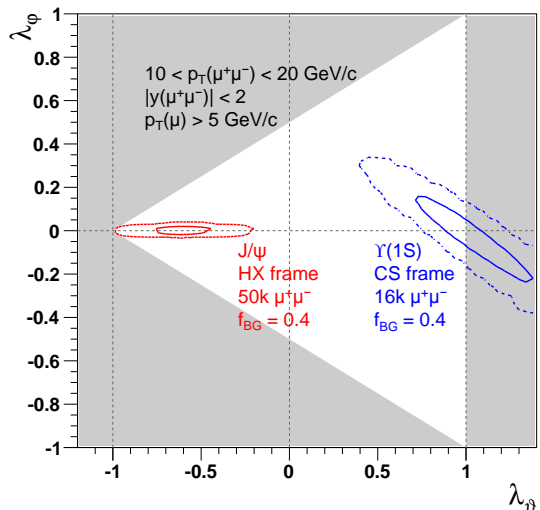


FIG. 4. Results of pseudo-measurements of the prompt- J/ψ and $\Upsilon(1S)$ dilepton decay distributions in Pb-Pb collisions, according to the corresponding scenarios discussed in the text. The background fraction (f_{BG}) is defined within $\pm 2\sigma$ from the maximum of the invariant mass distribution, where σ , the experimental width, is, respectively, 4 and 10 MeV/c^2 . The contours represent 68 and 99% confidence levels. The shaded area is physically forbidden.

measurement can be made in pp collisions, merging the χ_{c1} and χ_{c2} contributions and using the simplified procedure illustrated in Sec. IV (Eq. 4).

As a simpler option, a test of the sequential suppression pattern can be made by comparing the prompt- J/ψ polarization measured in pp collisions (or peripheral nucleus-nucleus) with the one measured in central nucleus-nucleus collisions and checking that this latter tends to the polarization of the ψ' , also measured in pp collisions.

In this illustration we have neglected the role of the ψ' suppression, which, in the sequential suppression scenario, would lead to a slight increase of $R(\chi_c)$ (and, therefore, to a slight reduction of the prompt- J/ψ polarization) *before* the χ_c disappearance. This would make the change in polarization due to χ_c suppression more drastic as a function of N_{part} , but would not modify the difference between the prompt- J/ψ polarizations observed in proton-proton and central nucleus-nucleus collisions.

Moreover, we are assuming that the parton recombination into low- p_T J/ψ in central collisions does not play a role. For this reason, in what follows we will consider relatively high- p_T measurements. However, we remark that recombination would probably change the above picture in a distinctive way, leading to a second observable change in the J/ψ polarization as a function of centrality.

The same method can be applied to the measurement of χ_b suppression using $\Upsilon(1S)$ polarization. According to the scenario based on the E866 data (Sec. III), in pp (and peripheral Pb-Pb) collisions the $\Upsilon(1S)$ should be only slightly polarized, reflecting the mixture of directly and

indirectly produced states with opposite polarizations. In central Pb-Pb collisions the $\Upsilon(1S)$ would acquire the fully transverse polarization characteristic of the directly produced S states, indicating the suppression of the P states. Also in this case the simple stepwise behaviour as a function of N_{part} would be slightly contaminated, but not made less visible, by the suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$. On the other hand, the presence of the $2P$ states in the bottomonium family would add an intermediate step in the pattern of polarization change.

Figure 4 shows the results of pseudo-measurements of the prompt- J/ψ and $\Upsilon(1S)$ polarizations in central Pb-Pb collisions, based on, respectively, about 30k and 10k reconstructed signal events in the dimuon channel and assuming in both cases a background fraction of 40%. The dimuon p_T and rapidity are in the ranges $10 < p_T < 20$ GeV/ c and $|y| < 2$. Only events where both muons have $p_T > 5$ GeV/ c are included in the reconstruction, in order to simulate the typical reduction of angular phase-space affecting this kind of measurements at the LHC. The central values of the measurements correspond to the expected polarizations, strongly longitudinal and fully transverse in the two respective scenarios, after the melting of the χ states. The results exclude large part of the $(\lambda_\vartheta, \lambda_\varphi)$ plane and, in particular, the region around the origin, containing the (precisely determined) pp values ($\lambda_\vartheta \sim -0.15$ in the J/ψ scenario and $\lambda_\vartheta \sim 0.3$ in the $\Upsilon(1S)$ scenario, assuming $R(\chi_b) \simeq 0.4$). Such measurements would represent a significant indication of the nuclear disassociation of the χ states.

VI. SUMMARY

We have demonstrated that it is possible to determine the nuclear suppression of the χ_c and χ_b states through measurements of the inclusive dilepton decay distributions of prompt J/ψ and $\Upsilon(1S)$.

In a preliminary discussion we have illustrated how the polarizations of the directly produced S - and P -state quarkonia are likely to differ significantly from one another. Given that the feed-down contributions of P states to the prompt S states are large, this means that there must be a measurable difference between the de-

cay distributions of indirectly and directly produced S states. The hypothesis is strongly supported by the E866 Υ data and is seen to reconcile the CDF prompt- J/ψ and $\Upsilon(1S)$ measurements with perturbative-QCD predictions for the polarizations of the directly produced states. These are interesting indications for the understanding of quarkonium production and should be verified with detailed polarization measurements distinguishing between the properties of directly and indirectly produced states. We have also proposed an alternative and simplified way of determining the polarizations of J/ψ and $\Upsilon(1S)$ coming from decays of P states, using measurements of $R(P)$ and of the polarizations of the $1S$ and $2/3S$ states, instead of studying directly the angular distribution of events identified with the presence of a radiated photon.

With the above premises, we have shown that a change in the relative yield of S and P states from proton-proton to nucleus-nucleus collisions is directly reflected in an observable change of the prompt- J/ψ [or $\Upsilon(1S)$] polarization. The sequential dissociation scenario has a particularly clean polarization signature: the melting of the χ states would be signalled by the observation of a significantly larger prompt- J/ψ [$\Upsilon(1S)$] polarization than the one measured in pp collision. After the complete suppression of χ production, the polarization should approach the one measured (in pp collisions) for the ψ' [$\Upsilon(2/3S)$].

In conclusion, quarkonium polarization can be used as a new probe for the formation of a deconfined medium. This method, based on the study of dilepton kinematics alone, provides a feasible and clean alternative to the direct measurement of the χ yields through reconstruction of radiative decays. With sizeable J/ψ and $\Upsilon(1S)$ event samples to be collected in nucleus-nucleus collisions, the LHC experiments have the potential to provide a clear insight into the role of the χ states in the dissociation of quarkonia, taking a crucial step forward in establishing the validity of the sequential melting mechanism.

We acknowledge support from Fundação para a Ciência e a Tecnologia, Portugal, under contracts SFRH/BPD/42343/2007, CERN/FP/116367/2010 and CERN/FP/116379/2010. We also acknowledge interesting discussions with C. Lourenço.

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