A penetrating look at Quark-Gluon Plasma physics
Probing the QCD phase transition with heavy quarkonia

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A small fraction of the results recently released by CMS in the field of quarkonium production in pp and Pb-Pb collisions are briefly presented.

The theory and experimental studies of quarkonium production and suppression as a laboratory to understand the QCD phase transition were triggered by Matsui and Satz\textsuperscript{1}, just before the first heavy-ion collisions at the CERN SPS took place. Today we know that the statement “$J/\psi$ suppression in nuclear collisions should provide an unambiguous signature of QGP formation” was somewhat naive, but the basic idea has survived: screening the QCD potential “dissolves” the charmonium and bottomonium bound states; and quarkonium states of different binding energies should dissolve at successive thresholds in the temperature of the medium, leading to a sequential suppression pattern\textsuperscript{2} that should work as a “thermometer” of the QCD matter. The following years much more has been understood regarding quarkonium production as a laboratory to understand hadron formation and QCD confinement (for recent reviews, see Refs.\textsuperscript{3,4} and references therein). But the mechanisms behind quarkonium production remain a challenge, even in the “elementary” case of pp collisions, the non-perturbative QCD aspects preventing a clear understanding of the strong interactions binding the quarks into hadrons. Non-relativistic QCD (NRQCD)\textsuperscript{5} is seemingly our best path towards efficient progress in this area of QCD phenomenology. In this framework, quarkonia are produced from the binding of quark-antiquark pairs created with a variety of quantum numbers, in colour singlet or octet configurations. These terms are characterized by significantly different kinematic dependences and polarizations, determined by the short-distance cross sections (SDCs), presently calculated at next-to-leading order (NLO). They contribute with probabilities proportional to long distance matrix elements (LDMEs), extracted from fits to experimental data\textsuperscript{6,7,8,9}. Traditionally, these “global fits” only consider the measured cross sections and then predict that quarkonia produced with high transverse momentum should be transversely polarized, in clear conflict with measurements, a situation dubbed “the quarkonium polarization puzzle”. The reluctance in using polarization data in the fits reflects the observation that most of the pre-LHC measurements are incomplete and ambiguous\textsuperscript{10}. Indeed, polarization measurements are very complex and
require exceptional care in the corresponding data analyses. The experimental situation has dramatically improved with the availability of high quality polarization measurements, using much-improved analysis approaches\textsuperscript{11,12} by CMS for the five $S$-wave quarkonium states\textsuperscript{13,14} and by LHCb for the charmonia\textsuperscript{15,16}. These results are at the basis of a new understanding of quarkonium production\textsuperscript{17}, dominated by the unpolarized $^{1}S_{0}^{(8)}$ pre-resonance octet term.

The CMS experiment\textsuperscript{18} has an excellent performance for studies of quarkonium production in the dimuon decay channel, both in pp and in Pb-Pb collisions, mostly thanks to its very large and high-granularity silicon tracker, very strong magnetic field, broad acceptance in absolute rapidity $|y|$ and in transverse momentum $p_T$, flexible trigger capabilities, and powerful data acquisition system. It is worth mentioning the good vertexing capabilities, allowing for a reliable subtraction of charmonium events resulting from B meson decays, so that the measurements always refer to “prompt” production. However, except for the $\psi(2S)$ case, all measured $S$-wave states add to the directly produced mesons a contribution from feed-down decays of heavier quarkonia, sometimes through several cascade steps. While the $J/\psi$ peak is always well above the underlying dimuon continuum, the $\psi(2S)$ peak is harder to see, especially at forward rapidity (worse dimuon mass resolution) and low $p_T$ (larger background)\textsuperscript{19}. The $\Upsilon(1S)$ peak is also easy to identify, with a good signal-to-background ratio, as shown in Fig. 1-left. The $\Upsilon(2S)$ resonance, well visible in the pp data, is much harder to see in the Pb-Pb data, clearly affected by a significant suppression; and there are no signs of $\Upsilon(3S)$ production in Pb-Pb collisions, in the data samples collected so far by CMS\textsuperscript{20}. It is worth noting that the nucleon-nucleon integrated luminosity of the existing Pb-Pb samples (351 $\mu$b\textsuperscript{-1} scaled by 208 squared) is not negligible, being more than half of that of the pp sample (25.8 pb\textsuperscript{-1}). Figure 1-right shows the $\Upsilon(2S)$ over $\Upsilon(1S)$ “double ratio”, comparing Pb-Pb to pp production in nine Pb-Pb centrality bins, including three bins in the “peripheral region” (50 to 100% centrality percentile). It is remarkable that this suppression pattern is essentially flat, at around 0.35, and the drop from pp to Pb-Pb occurs at very peripheral collisions. Also the $\psi(2S)$ is significantly more suppressed than the $J/\psi$, even in the most peripheral Pb-Pb collisions probed by CMS, for $|y| < 1.6$ and $p_T > 6.5$ GeV. Finally, the $\Upsilon(3S)$ over $\Upsilon(1S)$ double ratio is not significantly higher than zero, even in the most peripheral bin available to CMS with the current level of Pb-Pb integrated luminosity.

![Figure 1](https://example.com/figure1.png)

**Figure 1** – Left: Dimuon mass distribution in the $\Upsilon$ mass region, comparing the Pb-Pb data with the shape extrapolated from pp data, to illustrate the magnitude of the suppression affecting the excited states. Right: $\Upsilon(2S)$ over $\Upsilon(1S)$ and $\psi(2S)$ over $J/\psi$ double ratios as a function of Pb-Pb centrality.

The CMS collaboration has also reported results on “normalized single ratios”, denoted by $R_{AA}$, where the Pb-Pb and pp yields are directly compared for individual quarkonia\textsuperscript{21,22,23}. Figure 2-left shows the measured Pb-Pb to pp suppression levels, from data collected at 2.76 TeV,
for the five S-wave quarkonia, as a function of their binding energy. The most loosely bound state and the only one not affected by feed-down decays, the $\psi(2S)$, shows a very strong suppression. To appreciate how the suppression fades away as the binding energy increases, one would need to account for the feed-down contributions of the other onia states: maybe none of the directly produced $\Upsilon(1S)$ are suppressed and we are seeing a strong suppression of the heavier (S- and P-wave) bottomonia.

A clear and unambiguous understanding of quarkonium suppression also needs to account for polarization effects: we could observe quarkonium suppression simply because the mesons would be produced more transversely polarized in Pb-Pb than in pp, given that the acceptances are corrected assuming identical polarizations for all collision systems. So far, no measurements exist of quarkonium polarization in Pb-Pb collisions. CMS took a first step in that direction by measuring how the polarizations of the $\Upsilon(nS)$ states change with the number of charged particles, $N_{ch}$, produced in pp collisions. The measurements do not show significant variations of $\lambda_\theta$ with $N_{ch}$, but the large $\Upsilon(2S)$ and $\Upsilon(3S)$ uncertainties preclude definite statements in these cases and the interpretation of the result for the $\Upsilon(1S)$ state, shown in Fig. 2-right, is blurred by potential effects of the P-wave feed-down contributions, presently impossible to evaluate for lack of information regarding the $\chi_b(nP)$ polarizations and their feed-down fractions. The curves in the figure illustrate how the inclusive polarization might change as a function of $N_{ch}$ if the directly-produced component (of polarization $\lambda_0$) is complemented by a feed-down component (of polarization $\lambda_1$) that contributes with a fraction $f$, decreasing linearly with $N_{ch}$ from 50% to 0 in the $0 < N_{ch} < 60$ range. The six curves correspond to different assumptions for $\lambda_0$ and $\lambda_1$, reported in the legends, with $\lambda_1$ representing an effective average of the $\chi_b1$ and $\chi_b2$ polarizations (the $\chi_b$ and $\chi_b2$ values must verify $\lambda_\theta > -1/3$ and $\lambda_\theta > -3/5$, respectively). In these scenarios the feed-down fraction is assumed to become negligible at high $N_{ch}$, where the inclusive $\lambda_\theta$ tends to the direct $\lambda_0$ value. At low $N_{ch}$, where the feed-down contribution is, hypothetically, the highest, the inclusive $\lambda_\theta$ parameter crucially depends on the assumed $\chi_b$ polarization.

In conclusion, very interesting measurements have been made at the LHC, in particular by the CMS experiment, in the field of quarkonium production, both with pp and Pb-Pb data samples. Future results, especially involving the P-wave states (polarizations, feed-down fractions), are eagerly awaited. The improved understanding of quarkonium production in pp collisions will certainly help using quarkonia as probes of the QCD phase transition in Pb-Pb data.
References