Evidence for X(3872) in PbPb collisions and studies of its prompt production at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with CMS

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Abstract. The first evidence for X(3872) production in relativistic heavy ion collisions, with a significance of 4.2 standard deviations, is reported. The X(3872) production is studied in lead-lead (PbPb) collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV per nucleon pair with the CMS detector. The measurement is performed in the rapidity and transverse momentum ranges $|y| < 1.6$ and $15 < p_{\mathrm{T}} < 50$ GeV/c. The prompt X(3872) to ψ(2S) yield ratio is found to be $\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49(\mathrm{stat.}) \pm 0.52(\mathrm{syst.})$, to be compared with typical values of 0.1 for pp collisions. This provides new input to theoretical models of the X(3872) production mechanism, and of the nature of this exotic state.

The X(3872) is an exotic particle that was first observed in electron-position (e^+e^-) collision by Belle [1], and studied by experiments at hadron colliders [2–6] and e^+e^- [7, 8]. The quantum numbers of the X(3872) have been narrowed down by CDF [9], and later determined to be $J^{PC} = 1^{++}$ by LHCb [10]. However, the inner structure of X(3872) is still not yet fully understood. Interpretations in terms of charmonium, $\mathrm{D}^*(2010)^0\overline{\mathrm{D}}^0$ molecules [11], tetraquark states [12], and their admixture [13] have been proposed. The production and survival of the X(3872) in a quark-gluon plasma (QGP, a deconfined state of quarks and gluons [14, 15]), or in a later hadronic phase, is expected to depend upon the X(3872)'s internal structure [16–18]. Thus, the recent large data set of lead-lead (PbPb) collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV per nucleon pair, delivered by the Large Hadron Collider (LHC) at CERN at the end of 2018, opened new opportunities to probe the nature of this exotic state [19–22].

It is expected that in relativistic heavy ion collisions, the formation of the QGP could enhance or suppress the production of the X(3872) particle. Coalescence mechanisms could enhance the X(3872) production yield [17, 19]. These mechanisms can be modeled via the overlap of the density matrix of the constituents in an emission source with the Wigner function of the produced particle [23]. Therefore, the enhancement of the X(3872) production in the QGP would depend on the spatial configuration of the exotic state. Moreover, a longer distance between the quarks and antiquarks that constitute the state could also lead to a higher X(3872) dissociation rate, similar to that from the mechanism of quarkonium suppression in heavy ion collisions [24]. Therefore, the study of the X(3872) state in the QGP may be used as a tool to distinguish a compact tetraquark configuration with a radius ~0.3 fm from a molecular state with a radius greater than 1.5 fm [25]. Such a measurement would be complementary to the recent evidence for the radiative decay X(3872) $\rightarrow \psi(2\mathrm{S})\gamma$ in proton-proton (pp) collisions reported by LHCb Collaboration [26], which does not support a pure $\mathrm{D}^*(2010)^0\overline{\mathrm{D}}$ molecular interpretation. In addition, measurements of prompt X(3872) production could

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provide an interesting test of the statistical hadronization model [27], which assumes that the produced matter is in thermodynamic equilibrium at the phase transition to hadrons [28, 29].

In this proceedings, the first evidence for X(3872) production in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$ is reported. The PbPb sample corresponds to an integrated luminosity of 1.7nb^{-1}. The X(3872) candidates are reconstructed through the decay chain $\text{X}(3872) \to \text{J}/\psi(1\text{S})\,\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$, and are measured in the $15 < p_{\rm T} < 50\,\text{GeV}/c$ and $|y| < 1.6$ kinematic interval. At the LHC energies, the inclusive X(3872) yields in pp and PbPb collisions contain a significant nonprompt contribution coming from B hadron decays [6]. The nonprompt X(3872) component is related to the beauty quark energy loss and medium-modified B hadron production in heavy ion collisions, which has been studied with b-jets [30] and fully reconstructed B mesons [31]. Here, we focus on the prompt component, from charm quark fragmentation, for which the ratio ρ^i (i is pp or PbPb) between the corrected yields of X(3872) and ψ(2S) mesons (where the ψ(2S) is reconstructed with the same final-state particles in order to reduce systematic uncertainties) is presented: $\rho^i = \frac{N_i^{\text{X}(3872)\to \text{J}/\psi(1\text{S})\pi\pi}}{N_i^{\psi(2\text{S})\to \text{J}/\psi(1\text{S})\pi\pi}}$. The ratios in pp and PbPb collisions are connected to the nuclear modification factors $R_{\rm AA}^{\text{X}(3872)}$ and $R_{\rm AA}^{\psi(2\text{S})}$ (the meson yield ratio in nucleus-nucleus and pp interactions normalized by the number of inelastic nucleon-nucleon collisions) via the following relation: $\rho^{\rm PbPb} = \rho^{\rm pp}\frac{R_{\rm AA}^{\text{X}(3872)}}{R_{\rm AA}^{\psi(2\text{S})}}$.

The description of the CMS experiment and coordinate system can be found in Ref. [32] and the details on the analysis procedure are documented in Ref. [33]. The X(3872) and ψ(2S) signals are extracted from the $\text{J}/\psi(1\text{S})\,\pi^+\pi^-$ channel and $\text{J}/\psi(1\text{S})$ candidates are reconstructed by dimuon pairs. The raw inclusive yields of X(3872) and ψ(2S) are extracted by an extended unbinned maximum-likelihood fit. A double-Gaussian function with a common mean but independent widths is used to model each of the X(3872) and ψ(2S) peaks. For describing the combinatorial background, mostly from the random combination of a $\text{J}/\psi(1\text{S})$ candidate with other tracks, a 4$^{\text{th}}$-order polynomial is used, which gives the best fit in terms of χ^2 per degrees of freedom. The invariant mass fits, with offline selection optimized for X(3872), are shown in the left panel of Fig. 1. The significance of the inclusive X(3872) signal against background-only hypothesis is 4.2 standard deviations, which was calculated as the square root of the logarithm of the profile likelihood ratio where the signal is zero.

The contribution from B hadron decays is subtracted from the inclusive result using the pseudo-proper decay length l_{xy}, defined as the distance in the transverse plane, L_{xy}, between the vertex formed by the 4-tracks and the primary vertex, corrected by the transverse Lorentz boost of the candidate. After nonprompt contribution subtraction [33], the ratio $\rho^{\rm PbPb}$ between the prompt X(3872) and ψ(2S) mesons is shown in right panel of Fig. 1, together with $\rho^{\rm pp}$ measured as a function of $p_{\rm T}$. The pp data were measured at $\sqrt{s} = 7$ and $8\,\text{TeV}$, in the $|y| < 1.2$ and $|y| < 0.75$ intervals, respectively [5, 6, 10]. The 7 TeV result was derived using the CMS Collaboration published ratio of the inclusive yields [5] and prompt fractions [5, 34]. From Fig. 1 it is clear that the prompt $\rho^{\rm pp}$ does not depend significantly on collision energy or rapidity. In pp collisions at $\sqrt{s} = 8\,\text{TeV}$, in the kinematic range of $16 < p_{\rm T} < 22\,\text{GeV}/c$, the $\rho^{\rm pp}$ measured by ATLAS is $0.106 \pm 0.008(\text{stat.}) \pm 0.004(\text{syst.})$ [6]. This is to be compared to the prompt $\rho^{\rm PbPb}$ measured in this proceedings, $\rho^{\rm PbPb} = 1.08 \pm 0.49(\text{stat.}) \pm 0.52(\text{syst.})$.

In the interval $15 < p_{\rm T} < 20\,\text{GeV}/c$, the yield of the prompt ψ(2S) in PbPb collisions was reported to be significantly suppressed with respect to pp collisions, $R_{\rm AA}^{\psi(2\text{S})} = 0.142 \pm 0.061(\text{stat.}) \pm 0.020(\text{syst.})$ [35]. This leads to an $R_{\rm AA}^{\text{X}(3872)}$ central value larger than 1 (i.e., enhancement of the prompt X(3872) yield in PbPb compared to pp collisions). However, the uncertainties are such that $R_{\rm AA}^{\text{X}(3872)}$ is compatible with 1 within $\sim$1 standard deviation, and with $R_{\rm AA}^{\psi(2\text{S})}$ within $\sim$2 standard deviations. Thus, it is possible that in PbPb colli-

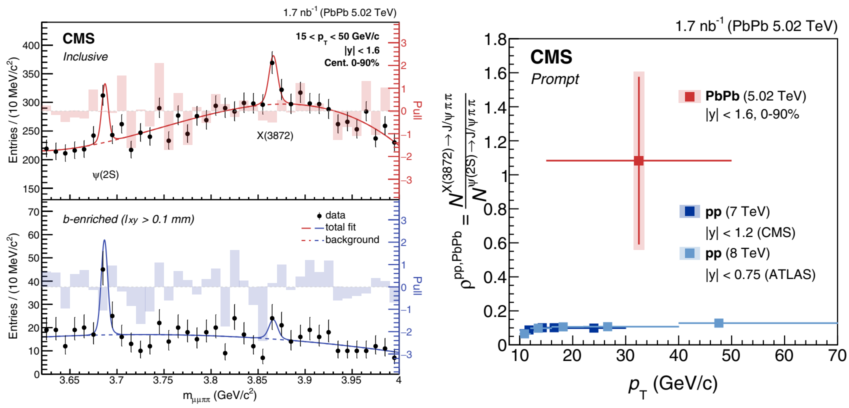

Figure 1. Left Panel: Invariant mass distribution of $m_{\mu\mu\pi\pi}$ in PbPb collisions, for the inclusive (upper) and B-enriched (bottom) samples. The vertical lines represent statistical uncertainties in the data. The pull distribution is represented by the shaded bars. Right Panel: ρ^{PbPb} in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. ρ^{pp} of prompt X(3872) over $\psi(2S)$ production in pp collisions at $\sqrt{s} = 8$ TeV, measured by ATLAS [6], and at $\sqrt{s} = 7$ TeV, measured by CMS [5] are also shown.

sions, the prompt X(3872) yield has either no suppression with respect to pp collisions, or as much suppression as the ψ(2S) state. The much larger data sample expected in Run 3 at the LHC will answer whether $R_{\mathrm{AA}}^{\mathrm{X(3872)}}$ is different from $R_{\mathrm{AA}}^{\psi(2\mathrm{S})}$ and significantly above unity. It may answer whether the ψ(2S) meson production (a bound state of a $\mathrm{q_c}$and $\overline{\mathrm{q}}_{\mathrm{c}}$ quarks, with $r \sim 0.9$ fm) [36], is affected differently by the medium produced in PbPb collisions than the X(3872) state (that could be made of $\mathrm{q_c}$, $\overline{\mathrm{q}}_{\mathrm{c}}$, $\mathrm{q_u}$, and $\overline{\mathrm{q}}_{\mathrm{u}}$ quarks, with a radius of $r \sim 0.3$ fm or $r > 1.5$ fm), the difference in both size and quark content playing a role into their production mechanisms. It will also answer whether the X(3872) prompt state production is different in PbPb collisions compared to pp collisions. It is also of great interest to compare the PbPb results to the studies of X(3872) and ψ(2S) production in pp collisions reported by LHCb [37], where a strong suppression of X(3872) to ψ(2S) ratio is observed at high multiplicity. Naively, if the suppression gets only stronger as a function of event multiplicity, we will see even stronger suppression in PbPb collisions. The fact that an evidence of X(3872) production is reported in this analysis may indicate additional mechanism which enhances the X(3872) production in the presence of the QGP.

The question whether X(3872) is a tetraquark or a molecule cannot yet be answered, because of the statistical limitation of the data, and the disagreement among models. For example, while the AMPT transport model [19] predicts $R_{\mathrm{AA}}^{\mathrm{molecule}} >> R_{\mathrm{AA}}^{\mathrm{tetraquark}}$ with $R_{\mathrm{AA}}^{\mathrm{molecule}} > 1$, the TAMU transport model [20] predicts $R_{\mathrm{AA}}^{\mathrm{molecule}} \sim R_{\mathrm{AA}}^{\mathrm{tetraquark}}/2$ (albeit, considering only the X(3872) from regeneration processes). With the further development of the theoretical models and high precision data from various collision systems from e^+e^-, electron-ion to heavy-ion collisions, we aim to determine the internal structure of the X(3872).

In summary, the first evidence for X(3872) production in heavy ion collisions is presented using lead-lead collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV per nucleon pair, recorded with the CMS detector. The significance of the inclusive X(3872) signal is 4.2 standard deviations. The ratio ρ^{PbPb} between the prompt X(3872) and ψ(2S) yields times their branching fractions into $\mathrm{J}/\psi(1\mathrm{S})\pi^+\pi^-$ is found to be $1.08 \pm 0.49(\mathrm{stat.}) \pm 0.52(\mathrm{syst.})$, to be compared with typical values of 0.1 for pp collisions. This result provides a unique experimental input to theoretical models of the X(3872) production mechanism, and of the nature of this exotic state.

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