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X(3872) Studies in LHC Run 3

Novel probes of Quark-Gluon Plasma medium

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Abstract. The X(3872) production is studied in proton-proton (p-p) collisions at a center-of-mass energy of $\sqrt{s} = 5.36\,\text{TeV}$, using the decay chain $X(3872) \rightarrow J/\psi\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$. The data were collected with the CMS detector in 2024 and correspond to an integrated luminosity of $455\,\text{pb}^{-1}$. The measurement is performed in the rapidity and transverse momentum ranges $|y| < 2.4$ and $p_T > 5\,\text{GeV/c}$. The X(3872) and $\psi(2S)$ ratio of cross section times branching fraction is $R = (7.60 \pm 0.52\,(\text{stat.}) \pm 1.10\,(\text{syst.})) \times 10^{-2}$. This study established the workflow and laid the groundwork for subsequent study in lead-lead (Pb–Pb) collisions.

Keywords: CMS, QGP, Exotic hadrons, X(3872), Charmonia, Cross section

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1 Introduction

1.1 Motivation

The X(3872) is an exotic state that was first observed by the Belle Collaboration in 2003 [1]. Many collaborations conducted research on X(3872) and made great progress. However, the nature of this exotic state is not yet fully understood. There are different interpretations of its structure, conventional charmonium, $D^*(2010)^0\bar{D}^0$ molecules[2], tetraquark states[3] and their admixture[4].
At the LHC, heavy-flavor hadrons are produced in abundance in both proton-proton (p-p) and lead-lead (Pb-Pb) collisions, allowing for detailed investigations of their production mechanisms, decay properties, and interactions with the surrounding medium. The study of X(3872) in heavy-ion collisions provides a unique opportunity to probe its internal structure and binding mechanism in the presence of a dense and colorful medium. If the state is a weakly bound hadronic molecule, it is expected to be more easily dissociated in the quark–gluon plasma, whereas a compact tetraquark interpretation would imply a higher survival probability. Therefore, relative and differential measurements of X(3872) against nearby charmonium states, namely $\Psi(2S)$, and across collision systems (pp vs PbPb) have the power to constrain its binding energy and pinpoint key QGP medium mechanisms that interfere with its formation, whether it is enhanced or suppressed. Such missing information shall allow to differentiate among the proposed models.
A previous study conducted a measurement of the nuclear modification factor of X(3872) based on LHC Run 2 Pb-Pb collisions. The data samples were collected by the CMS detector. However, there are not enough statistics, so the results had too large uncertainties to get a conclusion about X(3872)'s structure[5].
This study aims to explore the structure of X(3872) further with CMS Run 3 data. In this study, the workflow has been refined and preliminary results for p-p collisions have been finished, which has laid the groundwork for subsequent study of lead-lead (Pb–Pb) collisions.

1.2 The CMS detector

The Compact Muon Solenoid (CMS) is a general-purpose detector at the LHC. It has various physics goals includ-

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ing studying the Standard Model, searching for extra dimensions and dark matter. Although CMS has the same scientific goals as the ATLAS experiment, the technical solutions and magnet-system design are different.
The CMS detector has a cylindrical shape with 15m diameter and 21m in length. It has layered structure of several sub-detectors. A simplified schematics of the CMS detector is shown in Figure 1. The most relevant components for this project are the muon chambers and silicon trackers. Particles are reconstructed using algorithms that combine the signals provided by the subdetectors. A trigger system decides in real time whether to record events or discard them.
A detailed description of the CMS detector is found in [6].

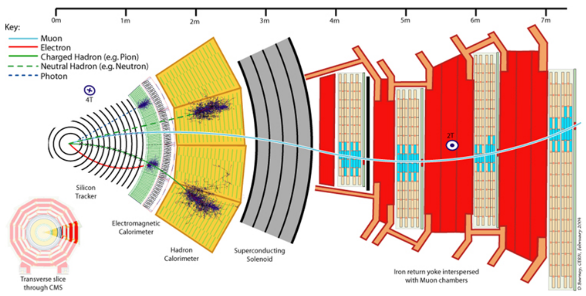

Figure 1. Schematic transverse view of the CMS detector

1.3 Relevant variables

Here is a list of the main variables that are used in this analysis.

- η : pseudorapidity;
- ϕ : angle of the trajectory of the object in the plane transverse to the direction of the proton beams;
- p_T : transverse momentum;
- M : invariant mass;
- Normalized Flight Length: 3D distance between the primary vertex (PV) and the secondary vertex (SV) where X(3872) is formed, normalized by its uncertainty;
- Normalized Flight Length in 2D: distance in the transverse plane between the primary vertex and secondary vertex, normalized by its uncertainty;
- Pointing Angle (α): opening angle between the PV– SV flight vector and the reconstructed X(3872) candidate momentum;
- Projected Pointing Angle (θ): opening angle between the reconstructed X(3872) momentum and the PV–SV vector projected onto the transverse plane (xy);
- dR: angular distance between each pion track and J/ψ .

2 Datasets

2.1 Dataset information

This study searches for a final state formed by a pair of muons along with two tracks. The muon pair forms the basis for event triggering. In this study, we use p-p collision data at a center-of-mass energy of $\sqrt{s} = 5.36\,\text{TeV}$, using the decay chain $X(3872) \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. The data were collected with the CMS detector in 2024 and correspond to an integrated luminosity of $455\,\text{pb}^{-1}$. The measurement is performed in the rapidity and transverse momentum ranges $|y| < 2.4$ and $p_T > 5\,\text{GeV}/c$.

2.2 pre-selections

2.2.1 Muon and J/ψ selection

The muon candidates are selected according to the *soft-muon* criteria. All muons candidates must fulfill the following acceptance selections:

$$\begin{aligned}
p_T^{\mu} &> 3.5\,\text{GeV}/c & &\text{for } |\eta^{\mu}| < 1.2\\
p_T^{\mu} &> (5.47 - 1.89\,|\eta^{\mu}|)\,\text{GeV}/c & &\text{for } 1.2 \le |\eta^{\mu}| < 2.1\\
p_T^{\mu} &> 1.5\,\text{GeV}/c & &\text{for } 2.1 \le |\eta^{\mu}| < 2.4
\end{aligned} \tag{1}$$

Finally, the surviving muon candidates are paired to form J/ψ candidates according to the following requirements:

- the two muons must feature opposite signs;
- the dimuon invariant mass has to be within 0.15 GeV from the PDG J/ψ mass;
- probability for the two muon tracks to originate from the same decay vertex > 1%.

2.2.2 Track selection

Track candidates, pions in the context of this study, were selected according to the following acceptance criteria:

- transverse momentum $p_T > 0.5\,\text{GeV}/c$,
- pseudorapidity $|\eta| < 2.4$,

and quality criteria:

- normalized uncertainty on the track p_T, $(\sigma_{p_T}/p_T) < 0.1$;
- sum of the numbers of Pixel and Strip hits $N_{\text{hits}} > 10$;
- χ^2/NDF probability divided by N_{hits}, < 0.18.

3 Event Selection

3.1 Sideband Region

The mass distribution after pre-selection cuts introduced above is shown in Figure 2. According to the distribution, we could define $3.66\,\text{GeV}/c^2 < m_{J/\psi\pi^+\pi^-} < 3.72\,\text{GeV}/c^2$ as the signal region for $\psi(2S)$, define $3.83\,\text{GeV}/c^2 < m_{J/\psi\pi^+\pi^-} < 3.91\,\text{GeV}/c^2$ as the signal region for X(3872) and define $3.6\,\text{GeV}/c^2 < m_{J/\psi\pi^+\pi^-} < 4.0\,\text{GeV}/c^2$ except the signal regions as sideband region.

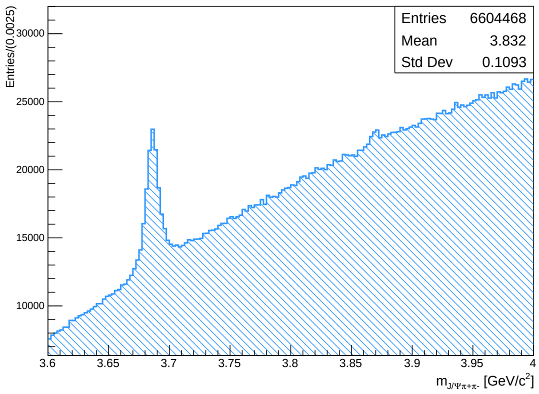

Figure 2. Mass distribution after pre-selection cuts

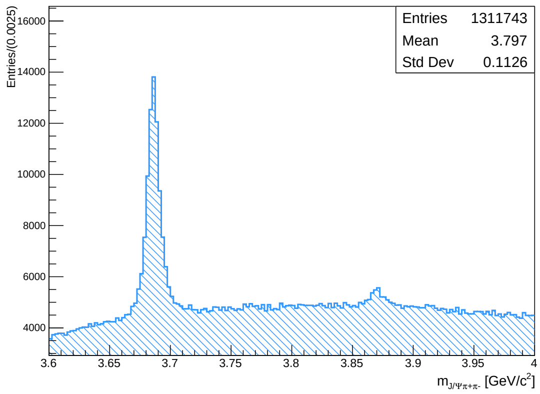

Figure 5. Mass distribution after pre-cuts

Under such definition, the mass distribution of signal events from MC samples and background events from sideband data samples is shown in Figure 3. There is no signal events at the edge of the signal regions, which proves our selection for signal regions is correct.

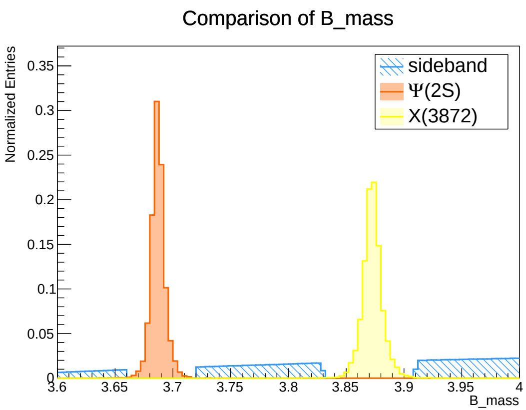

Figure 3. Mass distribution of signal and background events

3.2 Variable Distribution

The distributions of different variables for signal and background are shown in Figure 4.

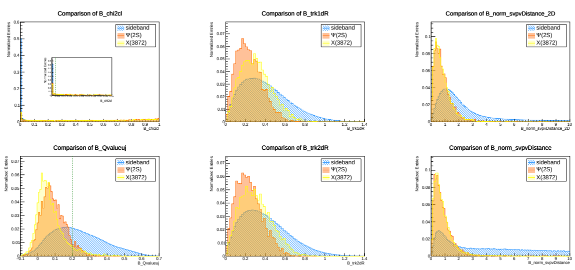

Figure 4. Variable distributions for signal and background

From the distributions, two pre-cuts are selected which are $B\_chi2cl > 0.003$ and $B\_Qvalueuj < 0.2$. The mass distribution after the pre-cuts are shown in Figure 5.

3.3 Optimization

To distinguish signal from background better, this study conducted single variable optimization on top of the pre-cuts. The way to optimize a certain variable is to maximize its figure of merit (FOM) which is defined in Equation 2. f_s and f_b are the scaling factors for signal and background. They are defined in Equation 3 and 4. S_{data} is the number of signal in data and S_{MC} is the number of MC events. B_{signal} is the number of background in the signal region. $B_{sideband}$ is the number of background in the sideband region. S_{data}, B_{signal} and $B_{sideband}$ are obtained from the fit.

$$FOM = \frac{f_s S}{\sqrt{f_s S + f_b B}} \tag{2}$$

$$f_s = \frac{S_{data}}{S_{MC}} \tag{3}$$

$$f_b = \frac{B_{signal}}{B_{sideband}} \tag{4}$$

In this study, the FOM for $\psi(2S)$ and X(3872) are calculated separately in order to compare their distributions, which should be similar. The cut that maximizes the FOM of X(3872) is the optimal cut for this variable. The distributions of FOM with respect to different variables are shown in Figure 6. Not all optimal cuts are chosen. Because the pre-cuts could distinguish signal from background well, only those optimal cuts that do not reject too many events and make the background smooth are chosen as selection cuts.

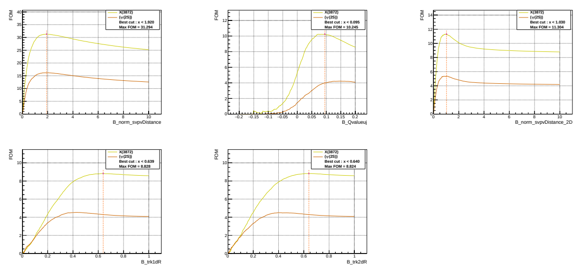

Figure 6. FOM distributions for $\psi(2S)$ and X(3872)

The optimal cuts chosen in this study are $B\_Qvalueuj < 0.095$, $B\_trk1dR < 0.639$ and $B\_trk2dR < 0.64$. After these optimal cuts on top of pre-cuts, the mass distribution is shown in Figure 7.

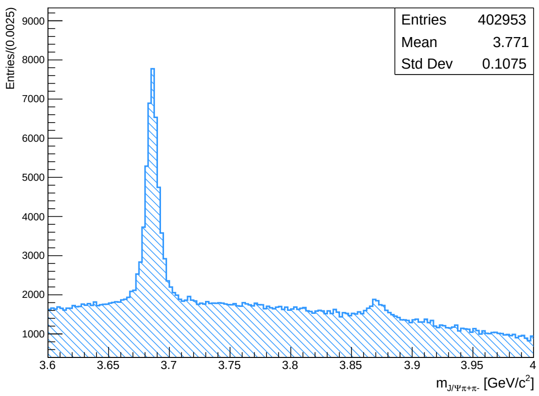

Figure 7. Mass distribution after optimal cuts

4 Cross Section

4.1 Signal Yield

In this study, the following fit model is adopted to get signal yield from data:

- $\psi(2S)$: double Gaussian with shared mean value
- $X(3872)$: single Gaussian
- background : third order Chebychev Polynomial

The fit result is shown in Figure 8. The yield of $\psi(2S)$ is $(3.11 \pm 0.03) \times 10^4$. The yield of X(3872) is $(2.87 \pm 0.19) \times 10^3$.

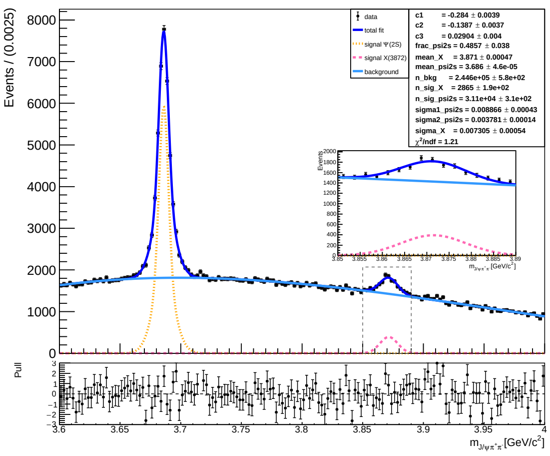

Figure 8. Mass fit result

4.2 Acceptance and Efficiency

The signal yield obtained from fit is the number of events which are reconstructed and selected. In order to measure the number of events that are produced by collisions, this study measured acceptance and efficiency to correct the yield. Acceptance and Efficiency are defined as:

$$A = \frac{N_{acc}}{N_{GEN}} , \tag{5}$$

$$\epsilon = \frac{N_{sel}}{N_{acc}} . \tag{6}$$

N_{GEN} is the number of events that are produced by collisions. N_{acc} is the number of events that are accepted and detected by CMS detector. N_{sel} is the number of events that are reconstructed and pass all the cuts.
In order to calculate acceptance and efficiency, a MC sample is produced. By applying cuts to this MC sample, the number of events before and after the cuts could be measured. Then acceptance and efficiency could be calculated by definition.

4.3 Cross Section and Ratio

The production cross section for a particle is an important physical observable which is defined in Equation 7,

$$\sigma = \frac{N}{A \times \epsilon \times \mathcal{B} \times L} . \tag{7}$$

N is signal yield obtained from the fit. A and ϵ are acceptance and efficiency which are determined from the MC sample. $\mathcal{B}$ is the branching fraction, which is obtained from PDG (Particle Data Group). L is the integrated luminosity of pp collision which is provided by the CMS collaboration.
The branching fraction for X(3872) to decay into $J/\psi\pi^+\pi^-$ has large uncertainties according to PDG [7]. Therefore, this study doesn't measure the cross sections. Instead, the ratio of the products of cross sections and branching fractions is measured as Equation 8 shows.

$$\begin{aligned} R &= \frac{\sigma(pp \to X(3872) + anything) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + anything) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)} \\ &= \frac{N_{X(3872)} \times A_{\psi(2S)} \times \epsilon_{\psi(2S)}}{N_{\psi(2S)} \times A_{X(3872)} \times \epsilon_{X(3872)}} \end{aligned} \tag{8}$$

5 Statistic and Systematic Uncertainties

5.1 Systematic Uncertainties

The systematic uncertainties which arise from alternative fit models are determined. Method 1 replaces the single Gaussian employed in the nominal method for fitting X(3872) with double Gaussian which uses a scaling factor times the sigmas used in the double Gaussian for fitting $\psi(2S)$. Method 2 replaces the single Gaussian employed in the nominal method for fitting X(3872) with double Gaussian. Method 3 replaces the third order Chebychev polynomial employed in the nominal method for fitting background with fourth order Chebychev polynomial. The fit results of these methods are shown in Figure 9.

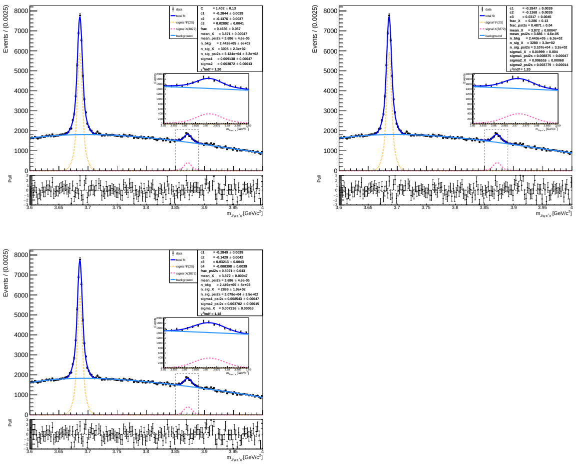

Figure 9. Different fit models for for $\psi(2S)$ and X(3872)

The systematic uncertainties from alternative fit models are the quadrature sum of the maximum uncertainties of signal and background model variations which are summarized in Table 1.

Table 1. Systematic Uncertainties

	$\psi(2S)$	X(3872)
Method 1	0.46%	4.89%
Method 2	0.09%	14.5%
Method 3	1.02%	0.15%
Total	1.12%	14.5%

5.2 Statistic Uncertainties

The statistic uncertainties which arise from fitted data are measured in Table 2.

Table 2. Systematic Uncertainties

	$\psi(2S)$	X(3872)
Total	1.01%	6.70%

6 Results and Conclusions

This study focuses on CMS Run 3 p-p data at $\sqrt{s}$ = 5.36 TeV. The main parts of this study are event selection, signal yield and uncertainties study. The result of this study is the ratio of the product of cross sections and branching fractions of X(3872) and $\psi(2S)$ which is $(7.60 \pm 0.52(stat.) \pm 1.10(syst.)) \times 10^{-2}$.
This study established the workflow for exploring X(3872) and measuring its property and laid the groundwork for subsequent study based on Pb–Pb collisions.

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References

[1] Belle Collaboration, Phys. Rev. Lett. **91**, 262001 (2003)
[2] N.A. Tornqvist, Phys. Lett. B **590**, 209 (2004), `hep-ph/0402237`
[3] L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, Phys. Rev. D **71**, 014028 (2005), `hep-ph/0412098`
[4] C. Hanhart, Y.S. Kalashnikova, A.V. Nefediev, Eur. Phys. J. A **47**, 101 (2011), `1106.1185`
[5] CMS Collaboration, Phys. Rev. Lett. **128**, 032001 (2022)
[6] CMS Collaboration, JINST **3**, S08004 (2008)
[7] S. Navas et al. (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)