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# Study of a B meson decay with X(3872) at the CMS experiment

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**Summary.** — This article is based on the talk I delivered on 16 September 2022, in the "Sezione Giovani" of the 108th National Congress of the Italian Physical Society, organized jointly with the Italian Association of Physics Students. A study of the exotic resonance X(3872) is presented, its production in the decay of neutral mesons is investigated using a sample of proton-proton collisions collected at $\sqrt{s} =$ 13 TeV with the CMS detector at the CERN LHC. This measurement, combined with analogue studies of the X(3872) production in charged B meson decays, can help to shed light on the puzzling nature of the X(3872) particle and in understanding QCD theory. The present analysis is currently under development and not yet approved by the CMS Collaboration.

## 1. – Introduction

$X(3872)$ is the first charmonium-like state ever observed which does not fit the standard quark model for charmonium. It has been observed, for the first time, in the decay of a charged $B$ meson at the Belle experiment [1]. Its mass is remarkably close to the sum of the $D^0$ and $\bar{D}^{0*}$ masses, suggesting that it could possibly be a loosely-bound molecule made of two charmed neutral mesons [2]. Alternatively, many recent studies explain several experimental observations of the $X(3872)$ with the hypothesis that it could be a tetraquark, a compact structure of a diquark and anti-diquark, which lies outside the conventional quark-model classification [3].

The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) put some important efforts in the study of the $X(3872)$. The branching fraction (BF) measurement of the $B_s^0 \to X(3872)\phi$ decay, observed for the first time [4], confirms, in the beauty-strange system, the relevantly lower BF for the neutral $B$ meson decays to $X(3872)$ plus a light meson with respect to that for the charged $B$ meson, a feature not

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observed in the corresponding decays to $\psi(2S)$ plus a light meson; this circumstance has found an explanation in the tetraquark scenario [5].

This analysis studies the $B^0 \rightarrow X(3872)\ K^0_s$ decay using the data collected by the CMS detector during 2017, corresponding to an integrated luminosity of 41 fb$^{-1}$ of proton-proton collisions at a center-of-mass-energy $\sqrt{s} = 13$ TeV. The channel of interest has been extensively studied in $B$-factories [6, 7].

The $X(3872)$ is reconstructed in its decays into a $J/\psi$ and a $\rho(770)$ meson which in turn decay to two muons and two oppositely charged pions respectively. The $K^0_s$ produces two pions of opposite charge, resulting in a final state with 6 particles,

$$B^0 \rightarrow X(3872)K^0_s \rightarrow J/\psi\rho(770)K^0_s \rightarrow \mu^+\mu^-\pi^+\pi^-\pi^+\pi^-. \tag{1}$$

The goal of the analysis is to measure the branching ratio of (1), via the following ratio:

$$\begin{aligned} R &= \frac{\mathcal{B}[B^0 \rightarrow X(3872)\ K^0_s]\cdot\mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[B^0 \rightarrow \psi(2S)\ K^0_s]\cdot\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]} \\ &= \frac{N[B^0 \rightarrow X(3872)\ K^0_s]}{\varepsilon_{B^0 \rightarrow X(3872)\ K^0_s}}\cdot\frac{\varepsilon_{B^0 \rightarrow \psi(2S)\ K^0_s}}{N[B^0 \rightarrow \psi(2S)\ K^0_s]}. \end{aligned} \tag{2}$$

The signal process is normalized to the $B^0 \rightarrow \psi(2S)\ K^0_s$ channel, which is known with a good precision: $\mathcal{B}[B^0 \rightarrow \psi(2S)K^0_s] = (2.90 \pm 0.25)\times 10^{-4}$ [8]. The two channels have the same final state $J/\psi\pi^+\pi^-K^0_s$ and, share strong similarities in terms of kinematics properties and topology of the decay. Thus, many systematic uncertainties are expected to cancel out in the ratio. Experimentally, the observable $R$ gets contributions only from the number of observed events, $N$, and the total reconstruction efficiency, $\varepsilon$, for both the signal and the normalization channel.

In this article, we illustrate the optimization of the analysis selection strategy, since it is still under development and the results are not yet public.

## 2. – Analysis strategy

The transverse momentum ($p_T$) of the pion tracks in $B^0 \rightarrow X(3872)\ K^0_s$ is of the order of hundreds of MeV, up to few GeV. Since a standard LHC collision usually contains hundreds of tracks, mostly in the low $p_T$ region, the rejection of the combinatorial background is one of the greatest challenges for this analysis.

To limit the impact of such a background, we put in place an event selection which aims to extract the signal decay chain.

The event selection starts by requiring two muons with $p_T > 4$ GeV, matching those that fired the online trigger and originating from the same interaction point in the CMS detector. Also, the invariant mass of the system is required to be compatible with the world-average $J/\psi$ mass $m^{PDG}_{J/\psi}$ [8]. The $J/\psi\pi^+\pi^-$ candidates are formed by combining the selected di-muon pair with all the oppositely charged tracks pairs in the event and must also satisfy some kinematic requirements. To reconstruct the possible $K^0_s$ candidates we combine all the oppositely charged tracks in the event and we reject those which are not compatible either with the common decay vertex hypothesis, or with the world-average $m^{PDG}_{K^0_s}$ within 200 MeV.

Two muons, two tracks and a neutral kaon candidate, selected as described, are combined together to build up $B^0 \rightarrow J/\psi\pi^+\pi^-K^0_s$ candidates. The common vertex

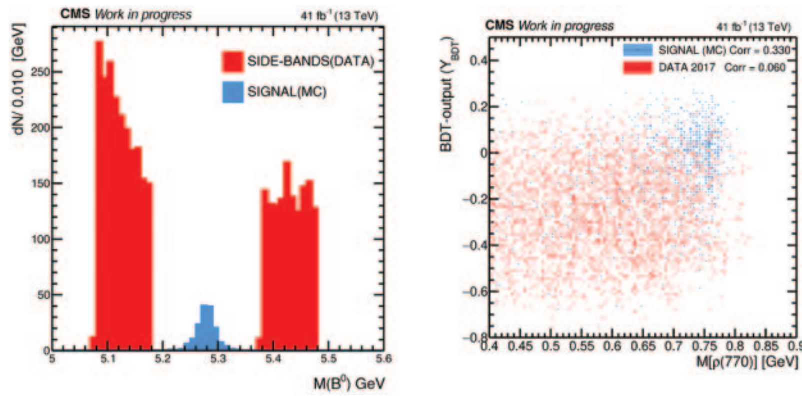


Fig. 1. – Left: $B^0$ candidates reconstructed invariant mass in MC simulation (blue) and in 2017 data (red); the latter distribution is shown only in the side-bands region. Right: two-dimensional distribution of the BDT-output and the invariant mass of the di-pion coming from the $\rho(770)$ decay, in MC-signal events (blue) and in data in the chosen mass side-bands (red).

resulting from a fit to the five tracks is required to be significantly displaced with respect to the $pp$ collision point taking into account the CMS tracker spatial resolution.

The outcome of this preselection on the simulated signal shows that most of the combinatorial background is associated to the dipion.

The signal selection is optimized using a Boosted Decision Tree (BDT) machine-learning algorithm. The BDT is trained to classify signal-like $B^0$ candidates over background-like ones, by processing a set of eight observables. We select the quantities that exhibit the best discriminant power and which are mostly related to the $B^0$ and the dipion kinematics. To train the algorithm we use the $B^0$ candidates reconstructed in the $B^0 \rightarrow X(3872)\ K_s^0$ simulation, as a signal sample, and the data taken from the $B^0$ mass side-bands, as a background sample. The distribution of the two samples is reported in the left-plot of fig. 1.

To enhance the discrimination power of the BDT algorithm, we study its output as a function of the mass of the di-pion system. The right-plot in fig. 1 shows how the signal events cluster in the top-right region of the plane. Starting from this two-dimensional distribution, we optimize a simultaneous cut on the BDT output and the $M_{\pi\pi}$ by maximizing the Punzi significance as the figure of merit [9]. The thresholds associated to the largest significance are $\bar{M}_{\pi\pi} > 700\,\text{MeV}$ and $\bar{y}_{BDT} > -0.08$. The selection is defined *versus* the signal sample.

The dynamics of the di-pion system is slightly different in the signal and in the normalization channel because of the different phase space available. After checking that the BDT response on the Monte Carlo of the $B^0 \rightarrow X(3872)\ K_s^0$ and $B^0 \rightarrow \psi(2S)\ K_s^0$ channels are sufficiently similar, the same BDT algorithm is applied also to select the $B^0 \rightarrow \psi(2S)\ K_s^0$ signal candidates. The selection on the $B^0 \rightarrow \psi(2S)\ K_s^0$ candidates is modified only by lowering the $M_{\pi\pi}$ threshold to 500 MeV.

On top of the preselection, the two-dimensional cut has an efficiency of 44.2% (34.0%) on the signal (normalization) channel and it is expected to reject the 97.2 % (88%) of the backgrounds with the $B^0 \rightarrow X(3872)\ K_s^0$ ($B^0 \rightarrow \psi(2S)\ K_s^0$ ) selection. The contribution of the background in the signal region, *i.e.*, the interval $[5.20, 5.35]$ GeV, is extrapolated from the integral of the fit-model to the $B$ meson sidebands in data. A

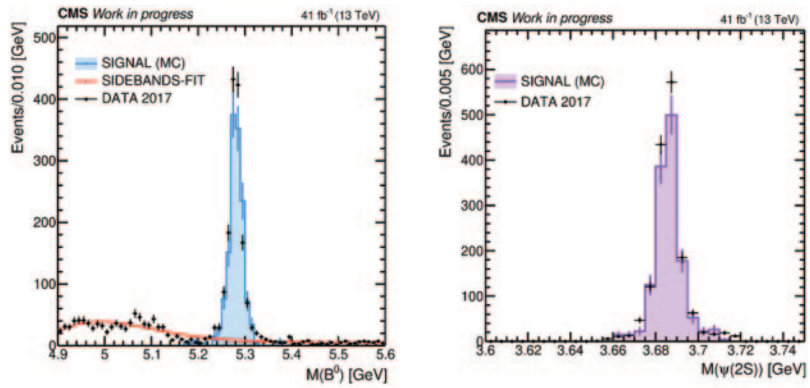


Fig. 2. – Results on the $B^0 \rightarrow \psi(2S)\ K_s^0$ channel. (left) $B^0$ invariant mass distribution after the application of the full selection (black dots). In blue the signal MC-sample and in red the fit to the data in the side-bands of the background function. (right) $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ reconstructed invariant mass distribution, in data and simulation after considering the reconstructed $B^0$ invariant mass within the signal region, *i.e.* 5.20 GeV $< M(B^0) <$ 5.35 GeV.

very good agreement between data and Monte Carlo is observed in the normalization channel (fig. 2), considering only the $B^0$ candidates whose reconstructed mass is in the signal region. For the signal channel, the signal region is still blinded.

## 3. – Conclusion and future prospects

This analysis aims to measure the branching fraction of the $B^0 \rightarrow X(3872)\ K_s^0$ decay. To improve the signal extraction, a multivariate analysis is designed.

The results obtained are promising and the good agreement between data and MC, obtained in the normalization channel ($B^0 \rightarrow \psi(2S)\ K_s^0$ ) analysis, demonstrates that they are reliable. To complete the analysis, we aim to perform a dedicated study of the systematic uncertainties sources and of the possible resonant backgrounds that could affect the signal region. Once they are understood, we will be able to include the full Run 2 data and open the data in the signal region to provide the first LHC measurement of the product of the branching fractions $\mathcal{B}[B^0 \rightarrow X(3872)\ K_s^0] \cdot \mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]$.

## REFERENCES

[1] Belle Collaboration, *Phys. Rev. Lett.*, **91** (2003) 262001.
[2] Guo F.-K. *et al.*, *Rev. Mod. Phys.*, **90** (2018) 015004.
[3] Maiani L. *et al.*, *Phys. Rev. D.*, **89** (2014) 114010.
[4] CMS Collaboration, *Phys. Rev. Lett.*, **125** (2020) 152001.
[5] Maiani L. *et al.*, *Phys. Rev. D.*, **102** (2020) 034017.
[6] Belle Collaboration, *Phys. Rev. D.*, **84** (2011) 052004.
[7] BaBar Collaboration, *Phys. Rev. D*, **82** (2010) 011101.
[8] Particle Data Group (Workman R. L. *et al.*), *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[9] Punzi G., arXiv:physics/0308063 (2003).