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# The $X(3872)$ and the search for its bottomonium counterpart at the LHC

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We present results on $X(3872)$ particle studies at three LHC experiments: ATLAS, CMS, and LHCb. Production cross section measurements are reported, as well as determination of the $X(3872)$ quantum numbers. The search of the $X(3872)$ bottomonium counterpart is also described.

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## 1. Introduction

The $X(3872)$ particle was first discovered by the Belle experiment in 2003 in the transition $B^{\pm} \to K^{\pm}X(\to J/\psi\pi^+\pi^-)$ [1] and soon was confirmed by many experiments [2]. The $X(3872)$ state is narrow, with mass close to the $D^0\bar{D}^{0*}$ threshold and decays to the $\rho^0 J/\psi$ and $\omega J/\psi$ final states with comparable branching fractions, thus violating isospin symmetry, so it cannot be a simple $c\bar{c}$ state. The nature of the state remains unclear, and there are many theoretical developments that suggest different models to describe the $X(3872)$ structure, see for example [3]. Heavy quark symmetry implies the existence of a hidden-beauty partner, $X_b$, which should be produced in $pp$ collisions.

In this paper we present the results by three LHC [4] experiments: ATLAS [5], CMS [6], and LHCb [7], related to the studies of $X(3872)$ properties and search for its bottomonium counterpart.

## 2. Search for $X_b$ at ATLAS and CMS

The decay $X_b \to \pi^+\pi^-\Upsilon(1S)(\to \mu^+\mu^-)$ may serve as a decay mode analogous to that in which the $X(3872)$ was discovered. CMS reported results on a search for this decay, finding no evidence for narrow states in the 10.06-10.31 GeV and 10.40-10.99 GeV mass ranges [8]. Upper limits on the product of cross section and branching fraction at values between 0.9% and 5.4% of the $\Upsilon(2S)$ rate were set. The resulting plot is shown in Figure 1 right. ATLAS has performed a similar search [9] with results shown in Figure 1 left, and no evidence for new narrow states with masses in the range 10.05-10.31 GeV and 10.40-11.00 GeV was found. Separate fits to the $\Upsilon(1^3\mathrm{D}_J)$ triplet, $\Upsilon(10860)$, and $\Upsilon(11020)$ also reveal no significant signals.

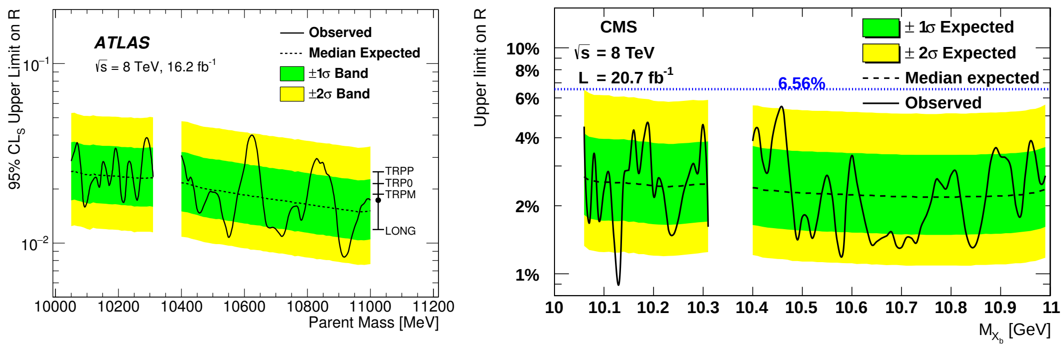


**Figure 1: Left:** Observed 95% $\mathrm{CL}_S$ upper limits (solid line) on the relative production rate $R = (\sigma B)/(\sigma B)_{2S}$ of a hypothetical $X_b$ parent state decaying isotropically to $\pi^+\pi^-\Upsilon(1S)$, as a function of mass. The median expectation (dashed) and the corresponding $\pm 1\sigma$ and $\pm 2\sigma$ bands (green and yellow respectively) are also shown. The bar on the right shows typical shifts under alternative $X_b$ spin-alignment scenarios, relative to the isotropic ("FLAT") case shown with the solid points [9]. **Right:** Upper limits at the 95% confidence level on $R$, the production cross section for the $X_b$ times its branching fraction to $\Upsilon(1S)\pi^+\pi^-$ relative to the $\Upsilon(2S)$, as a function of the $X_b$ mass. The solid curve shows the observed limits, while the dashed curve represents the expected limits in the absence of a signal, with the two shaded regions giving the $\pm 1$ and $\pm 2$ standard deviation uncertainties on the expected limits. The measured value for the analogous $X(3872)$ to $\psi(2S)$ ratio of 6.56% is shown by the dotted line [8].

## 3. Production measurement of $\psi(2S)$ and $X(3872)$ at ATLAS and CMS

A cross-section measurement of promptly produced $X(3872)$ was performed by CMS [10] at $\sqrt{s} = 7$ TeV as a function of transverse momentum $p_{\mathrm{T}}$. It was done in a kinematic range in which the $X(3872)$ had $(10 < p_{\mathrm{T}} < 50)$ GeV and rapidity $|y| < 1.2$. The ratio of the $X(3872)$ and $\psi(2S)$ cross sections times their branching fractions into $J/\psi\pi^+\pi^-$ was measured as a function of $p_{\mathrm{T}}$. It has been shown that the nonrelativistic QCD (NRQCD) prediction [11] for prompt $X(3872)$ production, assuming a $D^0\bar{D}^{*0}$ molecule, is too high, although the shape of the $p_{\mathrm{T}}$ dependence was described fairly well. A later interpretation of the $X(3872)$ as a mixed $\chi_{c1}(2P)-D^0\bar{D}^{*0}$ state, where the $X(3872)$ is produced predominantly through its $\chi_{c1}(2P)$ component, was adopted in conjunction with the next-to-leading-order (NLO) NRQCD model and fitted to CMS data, showing a good agreement [12]. ATLAS has performed a similar study at $\sqrt{s}=8$ TeV [13] with the $J/\psi\pi^+\pi^-$ candidates having $(10<p_T<70)$ GeV and $|y|<0.75$. Two models of the lifetime dependence of the non-prompt production are considered: a model with a single effective lifetime, and an alternative model with two distinctly different effective lifetimes. The two models give compatible results for the prompt and non-prompt differential cross sections of the $\psi(2S)$ and $X(3872)$. For the single-lifetime model, assuming that non-prompt $\psi(2S)$ and $X(3872)$ originate from the same mix of parent $b$-hadrons, the following result is obtained for the ratio of the branching fractions:

$$R_B^{1L}=\frac{\mathscr{B}(B\to X(3872)+\text{any})\mathscr{B}(X(3872)\to J/\psi\pi^+\pi^-)}{\mathscr{B}(B\to\psi(2S)+\text{any})\mathscr{B}(\psi(2S)\to J/\psi\pi^+\pi^-)}=(3.95\pm0.32(\text{stat})\pm0.08(\text{sys}))\times10^{-2},$$

[13]. In the two-lifetime model, the two lifetimes are fixed to expected values for $X(3872)$ originating from the decays of the $B_c$ and from long-lived $b$-hadrons, respectively, with their relative weight determined from the fits to the data. The ratio of the branching fractions $R_B$ is determined from the long-lived component alone:

$$R_B^{2L}=\frac{\mathscr{B}(B\to X(3872)+\text{any})\mathscr{B}(X(3872)\to J/\psi\pi^+\pi^-)}{\mathscr{B}(B\to\psi(2S)+\text{any})\mathscr{B}(\psi(2S)\to J/\psi\pi^+\pi^-)}=(3.57\pm0.33(\text{stat})\pm0.11(\text{sys}))\times10^{-2},$$

[13]. In the two-lifetime model, the fraction of the short-lived non-prompt component in $X(3872)$ production, for $p_T>10$ GeV, is found to be

$$\frac{\sigma(pp\to B_c+\text{any})\mathscr{B}(B_c\to X(3872)+\text{any})}{\sigma(pp\to\text{non-prompt }X(3872)+\text{any})}=(25\pm13(\text{stat})\pm2(\text{sys})\pm5(\text{spin}))\%, \tag{3.1}$$

[13]. The measured differential cross section for non-prompt production of the $X(3872)$ is shown in Figure 2 (right). This is compared to a calculation based on the FONLL model prediction for $\psi(2S)$, recalculated for the $X(3872)$ using a kinematic template [13] for the non-prompt $X(3872)/\psi(2S)$ ratio and the effective value of the product of the branching fractions $\mathscr{B}(B\to X(3872))\mathscr{B}(X(3872)\to J/\psi\pi^+\pi^-)=(1.9\pm0.8)\times10^{-4}$ estimated in Ref. 3.1 based on Tevatron data [15]. This calculation overestimates the data by a factor increasing with $p_T$ from about four to about eight over the $p_T$ range of this measurement. The non-prompt fractions of $\psi(2S)$ and $X(3872)$ production are shown in Figure 3. The non-prompt fraction of $X(3872)$ shows no sizeable dependence on $p_T$. This measurement agrees within uncertainties with the CMS result obtained at $\sqrt{s}=7$ TeV [10].

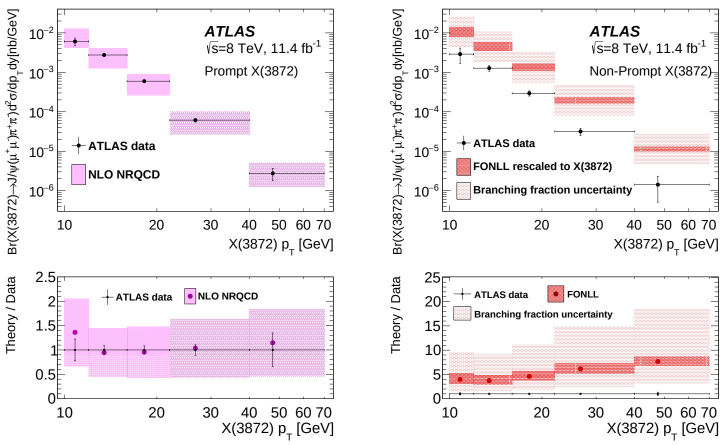


**Figure 2:** Measured cross section times branching fractions as a function of $p_T$ for (left) prompt $X(3872)$ in the ATLAS experiment [13] compared to NLO NRQCD predictions with the $X(3872)$ modelled as a mixture of $\chi_{c1}(2P)$ and a $D^0\bar{D}^{*0}$ molecular state [12], and (right) non-prompt $X(3872)$ compared to the FONLL [14] model prediction. Bottom plots on both left and right show theory to data ratio.

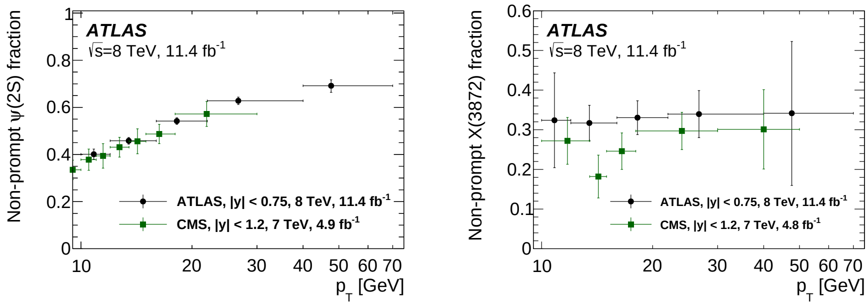


**Figure 3:** Measured non-prompt fractions for (left) $\psi(2S)$ and (right) $X(3872)$ production in the ATLAS experiment [13], compared to CMS results [10] at $\sqrt{s}$ = 7 TeV. The blue circles are the results reported by ATLAS, while the green squares show CMS results [10, 16].

## 4. Determination of the $X(3872)$ quantum numbers at LHCb

Early constraints on the $X(3872)$ quantum numbers were set by CDF [17] and have restricted the options to $1^{++}$ and $2^{-+}$. LHCb's 2013 full angular analysis [18] settled on $1^{++}$, but that analysis assumed that the lowest orbital angular momentum process dominated the decay. A new analysis [19] described below removed that assumption. The analysis uses 3 fb$^{-1}$ of $\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV data.

The $X(3872)$ signal is sought in the decay $B^+ \to X(3872)K^+$ with $X(3872) \to \rho^0 J/\psi$, $\rho^0 \to \pi^+\pi^-$, and $J/\psi \to \mu^+\mu^-$. The fit yields 1011 $\pm$ 38 signal events over a background of 1468 $\pm$ 44 in the $\Delta$M range of (725–825) MeV. The $X(3872)$ mass resolution is 2.8 MeV. The signal purity is 80% within 2.5 standard deviations around the peak.

Angular correlations in the $B^+$ decay chain are analyzed using an unbinned maximum-likelihood fit to determine the $X(3872)$ quantum numbers and orbital angular momentum. The probability density function ($\mathscr{P}$) for each $J^{PC}$ hypothesis, $J_X$, is defined in the five-dimensional angular space $\Omega \equiv (\cos\theta_X, \cos\theta_\rho, \Delta\phi_{X,\rho}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$, where $\theta_X$, $\theta_\rho$ and $\theta_{J/\psi}$ are the helicity angles in the $X(3872)$, $\rho^0$ and $J/\psi$ decays, respectively, and $\Delta\phi_{X,\rho}$ and $\Delta\phi_{X,J/\psi}$ are the angles between the decay planes of the $X(3872)$ particle and its decay products. The quantity $\mathscr{P}$ is the normalized product of the expected decay matrix element ($\mathscr{M}$) squared and the reconstruction efficiency ($\varepsilon$), $\mathscr{P}(\Omega|J_X) = |\mathscr{M}(\Omega|J_X)|^2\varepsilon(\Omega)/I(J_X)$, where $I(J_X) = \int|\mathscr{M}(\Omega|J_X)|^2\varepsilon(\Omega)d\Omega$. The efficiency is averaged over the $\pi^+\pi^-$ mass of the $X(3872) \to \rho^0 J/\psi$, $\rho^0 \to \pi^+\pi^-$ decay. The lineshape of the $\rho^0$ resonance can change slightly depending on the $X(3872)$ spin hypothesis. The effect on $\varepsilon(\Omega)$ is very small and is neglected. The angular correlations are obtained using the helicity formalism,

$$|\mathscr{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Bigg| \sum_{\lambda_{J/\psi},\lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi},\lambda_\rho}\; D^{J_X}_{0,\lambda_{J/\psi}-\lambda_\rho}(0,\theta_X,0)^* \\ D^1_{\lambda_\rho,0}(\Delta\phi_{X,\rho},\theta_\rho,0)^*\; D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\Delta\phi_{X,J/\psi},\theta_{J/\psi},0)^* \Bigg|^2,$$

where the $\lambda$'s are particle helicities, $\Delta\lambda_\mu = \lambda_{\mu^+} - \lambda_{\mu^-}$, and the $D^J_{\lambda_1,\lambda_2}$ are Wigner functions. The helicity couplings, $A_{\lambda_{J/\psi},\lambda_\rho}$, are expressed in terms of the $LS$ couplings, $B_{LS}$, through Clebsch-Gordan coefficients, where $L$ is the orbital angular momentum between the $\rho^0$ and the $J/\psi$ mesons, and $S$ is the sum of their spins. The possible values of $L$ are constrained by parity conservation, $P_X = P_{J/\psi}P_\rho(-1)^L = (-1)^L$. In this analysis all $L$ values are allowed. Values of $J_X$ up to four are analyzed. Since the orbital angular momentum in the $B^+$ decay equals $J_X$, high values are suppressed by the angular momentum barrier. The set of possible complex $B_{LS}$ amplitudes, which are free parameters in the fit, is denoted as $\alpha$. The function to be minimized is $-2\ln\mathscr{L}(J_X,\alpha) \equiv -s_w 2\sum_{i=1}^{N_{\rm data}} w_i \ln\mathscr{P}(\Omega_i|J_X,\alpha)$, where $\mathscr{L}(J_X,\alpha)$ is the unbinned likelihood and $N_{\rm data}$ is the number of selected candidates. The background is subtracted using the *sPlot* technique [20] by assigning a weight, $w_i$, to each candidate based on its $\Delta M$ value. No correlations between $\Delta M$ and $\Omega$ are observed. Prompt production of $X(3872)$ in $pp$ collisions gives negligible contribution to the selected sample. Statistical fluctuations in the background subtraction are taken into account in the log-likelihood value via a constant scaling factor, $s_w = \sum_{i=1}^{N_{\rm data}} w_i / \sum_{i=1}^{N_{\rm data}} {w_i}^2$. The $1^{++}$ hypothesis gives the highest likelihood value. Projections of the data and of the fit $\mathscr{P}$ onto individual angles show good consistency with the $1^{++}$ assignment as is illustrated in Fig. 4 left. Inconsistency with the other assignments is apparent when correlations between various angles are examined. For example, the data projection onto $\cos\theta_X$ is consistent only with the $1^{++}$ fit projection after requiring $|\cos\theta_\rho| > 0.6$ (see Fig. 4 right), while inconsistency with the other quantum number assignments is less clear without the $\cos\theta_\rho$ requirement.

In summary, the analysis confirms that the eigenvalues of total angular momentum, parity, and charge-conjugation of the $X(3872)$ state are $1^{++}$. These quantum numbers are consistent with those predicted by the molecular or tetraquark models and with the $\chi_{c1}(2^3\mathrm{P}_1)$ charmonium state [21], possibly mixed with a molecule [22]. Other charmonium states are excluded. No significant D–wave fraction is found, with an upper limit of 4% at 95% C.L. The S–wave dominance is expected in the charmonium or tetraquark models, in which the $X(3872)$ state has a compact size. An extended size, as that predicted by the molecular model, implies more favorable conditions for the D wave. However, conclusive discrimination among models is difficult because quantitative predictions are not available.



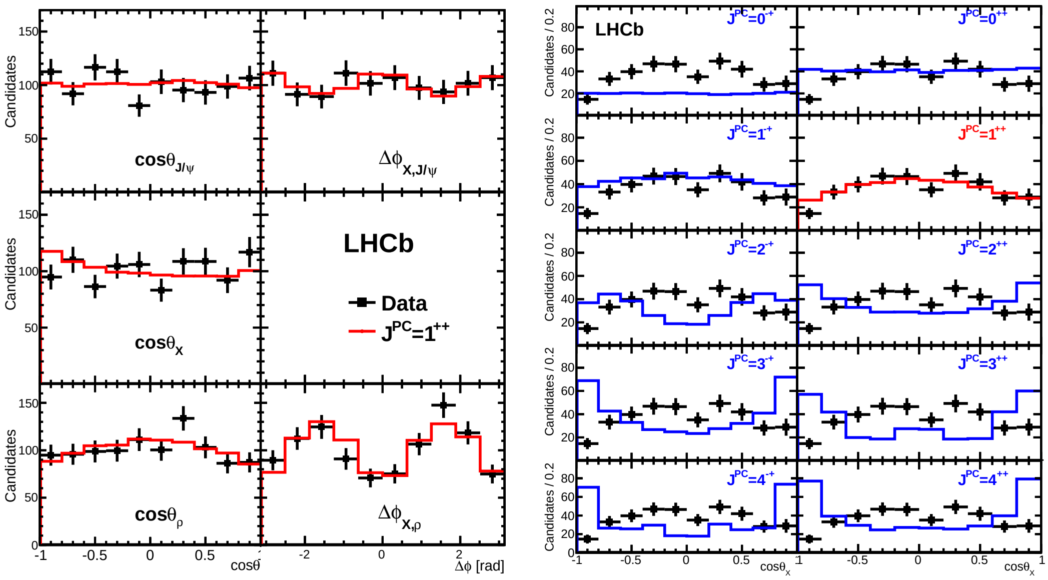


**Figure 4: Left:** Background-subtracted distributions of all angles for the data (points with error bars) and for the $1^{++}$ fit projections (solid histograms). **Right:** Background-subtracted distribution of $\cos\theta_X$ for candidates with $|\cos\theta_\rho| > 0.6$ for the data (points with error bars) compared to the expected distributions for various $X(3872)$ $J^{PC}$ assignments (solid histograms) with the $B_{LS}$ amplitudes obtained by the fit to the data in the five-dimensional angular space. The fit displays are normalized to the observed number of signal events in the full angular phase space.

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