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Observation and study of the $X(3872)$ particle with the CMS experiment at LHC(*)

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Summary. — The discovery of the $X(3872)$ resonance in the decay channel $J/\psi\pi^+\pi^-$ by the Belle Collaboration in 2003 opened up a new chapter in the QCD landscape. The properties of the $X(3872)$ are not in agreement with being a charmonium state. Different interpretations are still under study: one possibility is that the particle is a molecule of D^* mesons, another one is that it is a hybrid of bound states and another one is that it is a tetra-quark state. We report the study of the $X(3872)$ particle in the CMS experiment, at LHC, with 2010 data and a first view at 2011 data. The observed decay channel is that one into a J/ψ (reconstructed with an opposite sign muons pair) and an opposite sign pions pair ($\pi^+\pi^-$). The CMS experiment, one of the two general purpose experiments in the LHC collider, has an impressive performance in the tracks and muons detection and reconstruction due to its superior detectors performances. We show the measurement procedure of the production cross-section ratio of the $X(3872)$ and $\psi(2S)$ in the same decay channel, using the statistics collected by CMS at $\sqrt{s} = 7\,\text{TeV}$ in 2010, corresponding to $\sim 40\,\text{pb}^{-1}$ of integrated luminosity. The increased number of reconstructed $X(3872)$ in 2011 collisions, corresponding to an integrated luminosity of about $1\,\text{fb}^{-1}$, permits to continue the study of this particle.

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1. – Detector description

The Compact Muon Solenoid (CMS) is a general-purpose detector at the Large Hadron Collider (LHC) at CERN, near Geneva (Switzerland).

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The central feature of the apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T [1]. Within the field volume there are: a silicon pixel and strip tracker, a crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter. The inner tracker, made of 1440 silicon pixels and 15148 silicon strips detector modules, records charged particles within the $|\eta| < 2.5$ pseudorapidity([1]) range. Muons are measured in gas-ionization detectors embedded in the steel return yoke in the pseudo-rapidity window $|\eta| < 2.5$ and with detection planes made of drift tubes, cathode strip chambers and resistive plate chambers. Detector signals in the muon detectors are matched to measurements in the silicon tracker. The transverse momentum resolution for muons is $\sim 1\%$ for p_T of $10\,\mathrm{GeV}/c$.

A more detailed description of CMS can be found in ref. [2].

2. – Overview

The direct production of quarkonium states in the hadron collider, as in the LHC, is described in the framework of the NRQCD [3]. The quantitative prediction of this theory for the differential production cross-section of the $X(3872)$ have been confirmed for both $p\overline{p}$ collisions at the Tevatron and also pp collisions at the LHC.

As was found at the Tevatron, a hadron collider can provide a unique contribution to the study of this particle. The CMS detector and the large production rate allow study of the properties of the $X(3872)$. At the Tevatron the production of the $X(3872)$ in $p\overline{p}$ collisions was found to be dominantly prompt, without the typical lifetime signature indicating the presence of B mesons in the events. For the long-lived fraction, a branching ratio value of $16 \pm 4.9\%$ has been measured.

The goal of this analysis is the measurement of the ratio of the cross-section of the $X(3872)$ to the $\psi(2S)$, in the proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. The decays observed are: $X(3872)$, $\psi \to J/\psi\pi^+\pi^-$. The procedure is quite similar to that one adopted in the Tevatron experiments, CDF and D0 [4, 5].

In a first step the J/ψ candidates are reconstructed utilizing their decays into two oppositely charged muons. The branching ratio for this decay has the value of $5.93 \pm 0.06\%$ [6]. In a second step two pions are paired to the J/ψ to reconstruct the $X(3872)$ and the $\psi(2S)$.

The number of the $X(3872)$ and $\psi(2S)$ signal events is determined from the invariant mass spectrum, and it is used to calculate the ratio [1]

$$\frac{\sigma(pp \to X(3872) + \text{anything}) \times \mathrm{BR}(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times \mathrm{BR}(\psi(2S) \to J/\psi\pi^+\pi^-)}, \tag{1}$$

in this way the systematic errors mainly cancel out. The uncertainties simplified in the ratio are those related to the triggering and reconstruction of the J/ψ mesons and the external normalization error of the luminosity. The first is due to the efficiency of the muon reconstruction in the detector and the second is due to the measurement of the luminosity of LHC.

The remaining systematic uncertainties arise from the pion spectra of the two states, because they are different for the $X(3872)$ and for the $\psi(2S)$, in transverse momentum and in the angular distribution of the particles.

([1]) In the CMS convention the pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$ where θ is the polar angle measured from the z-axis which points along the counterclockwise beam direction.

In the measurement of the cross-section ratio, the differences in acceptance and efficiency are accounted for a factor determined by simulated events. In the future, a data-driven method will be used to verify the accuracy of the simulations.

Another important issue to study is the prompt and non-prompt components of the $X(3872)$. Further analysis, less limited by statistics, will permit better measurements of these fractions to be performed.

3. – Data analysis

The data are those collected in 2010 data run A and run B, corresponding to an integrated luminosity of $36\,\text{pb}^{-1}$. The triggers used were the *HLT_DoubleMu0*, which requires in the event two muons at the L3 trigger level [2] without a minimum p_T value and the *HLT_DoubleMu0_Quarkonium_v1*, which requires two muons with opposite charge and that the invariant mass of the muons system to be in the window from $1.5\,\text{GeV}/c^2$ to $14.5\,\text{GeV}/c^2$. These are used in different runs in order to optimize the yield of the $X(3872)$ and $\psi(2S)$.

3·1. $J/\psi \to \mu^+\mu^-$ *selection*. – The selection of the J/ψ candidate events is done with two identified muon candidates: tracker muons or global muons [7]. Events are selected with two identified muons of opposite charge consistent with the invariant mass of the J/ψ meson ($3096.916 \pm 0.011\,\text{MeV}/c^2$ [6]). In particular, the reconstructed inner tracks are required to have at least two hits in the pixel detector and at least twelve hits in the tracker system (pixel plus strip). The condition required for the track fit of the inner tracker is to have $\chi^2/\text{NDF} < 1.8$. Additional quality criteria are imposed to remove mostly the duplicate muon, called ghost, which comes from the same muon hits.

For the global muons it is required to leave at least one valid hit in the muon system. The total fit of the muons to the inner tracker and to the outer muon track yields must be $\chi^2/\text{NDF} < 20$. Finally the two muons are required to originate from a common vertex with a probability at least of 0.01. Also the muons identified must match with those that triggered the event.

The identified muons are also separated in three kinematic regions in the CMS detector, each of which have a specific requirement imposed. In the barrel region, $|\eta| < 1.3$, the muons must have $p_T > 3.3\,\text{GeV}/c$; in the intermediate region, $1.3 < |\eta| < 2.2$, they must have $p > 2.9\,\text{GeV}/c$ and in the endcap region, $|\eta| > 2.2$, they must have $p_T > 0.8\,\text{GeV}/c$; where p is the momentum, p_T is the transverse momentum and η is the pseudorapidity of the muon. These cuts require that the muons to be within the detector acceptance. This acceptance range is chosen to guarantee a single-muon detectability exceeding 10% [7]. In fig. 1 we show the kinematic characteristics of the J/ψ. About 2 million J/ψ are found, as shown in fig. 2. No explicit cuts on the J/ψ kinematics are applied.

3·1.1. $X(3872) \to (J/\psi \to)\mu^+\mu^-\pi^+\pi^-$ selection. In order to select the J/ψ candidate for further analysis, the invariant mass has been fitted with two functions (Crystal Ball and Gaussian [7]) in three rapidity regions. A window is defined in order to keep at least 99% of the signal. After the reconstruction of the J/ψ meson candidate, a pair of opposite charge pions is searched for. A refit of the four tracks is performed, constrained to originate from the same vertex and the dimuon system to have the mass of the J/ψ.

Pions tracks are required to have at least two hits in the pixel tracker detector, and five hits in the strip detector [1]. The transverse momentum of the pions, before the four tracks refit, is required to be larger than $400\,\text{MeV}/c$. The pion tracks that kinematically match with the muon tracks are removed. In this case, if the pion track is very close in

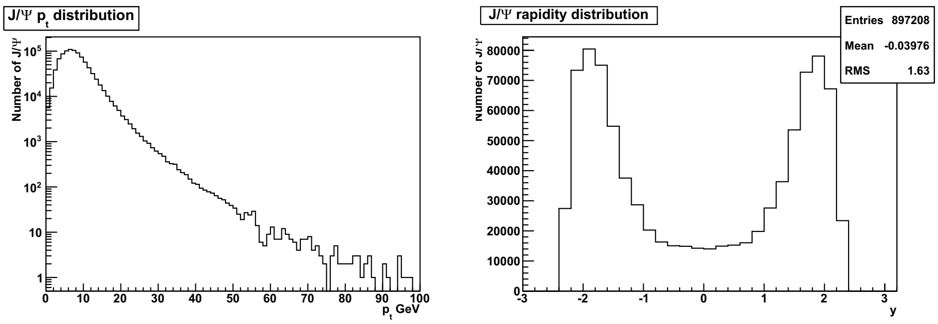

Fig. 1. – Kinematic characteristics for the J/ψ candidates as measured in data. Left, J/ψ p_T distribution (where GeV is meant to be GeV/c); right, J/ψ y, rapidity distribution.

space and in kinematic values to the muon track it is discarded. If the $\frac{|p^{\mu^{\rm rec}} - p^{\pi}|}{p^{\mu^{\rm rec}}} < 0.1$ (where p is the momentum of the tracks) and $\Delta R(\mu^{\rm rec}, \pi) < 0.5$ the tracks are the same, and have been discarded. The charge of the two pions is required to be opposite.

In fig. 3 the pions p_T (separately, the one with higher and the one with lower), after the four-track refit are shown.

The invariant mass of this system, $\mu^+\mu^-\pi^+\pi^-$, is required to be smaller than $5\,\mathrm{GeV}/c^2$.

The four-vertex fit probability is required to be larger than 0.01 in order to reduce the combinatorial background coming from tracks originating from different vertices.

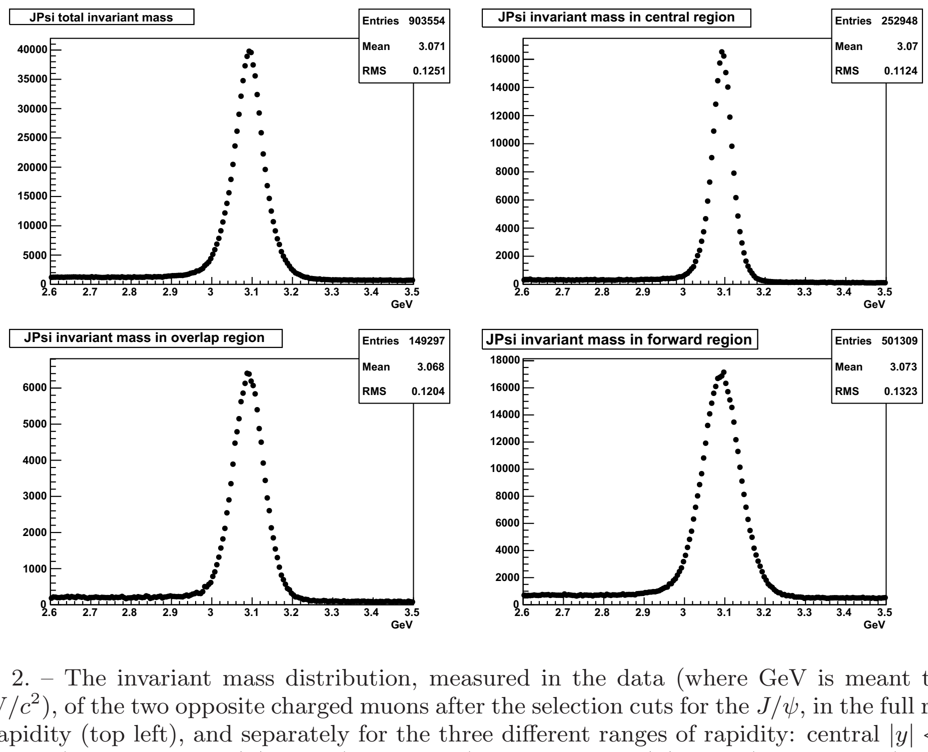

Fig. 2. – The invariant mass distribution, measured in the data (where GeV is meant to be GeV/c^2), of the two opposite charged muons after the selection cuts for the J/ψ, in the full range of rapidity (top left), and separately for the three different ranges of rapidity: central $|y| < 1.3$ (top right), overlap $1.3 < |y| < 2.2$ (bottom left), forward $2.2 < |y| < 2.4$ (bottom right).

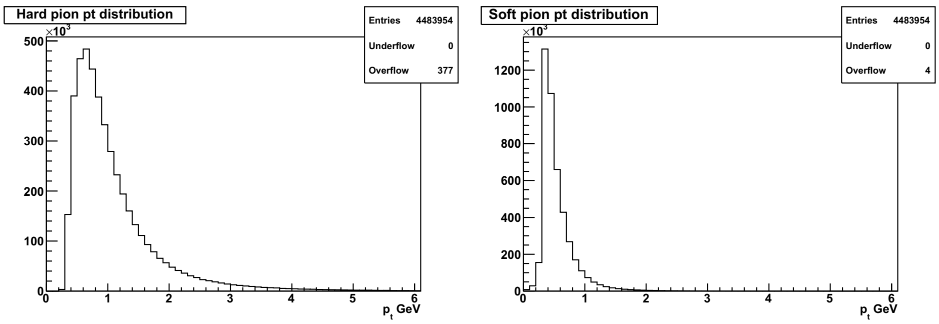

Fig. 3. – Distribution of p_T pions as measured in data (where GeV is meant to be GeV/c): right, the lower; left, the higher.

The probability of the vertex is not flat because the errors from the fits of the tracks are not correctly evaluated.

A cut on $\Delta R < 0.7$(2) between the J/ψ and each of the pions is applied.

To minimize the combinatorial background and with that increasing the signal-over-background ratio for the $X(3872)$ signal, $p_T(\pi^+\pi^-) > 1.5\,\mathrm{GeV}/c$ is required. The distributions of the ΔR and p_T of the pions pair are shown in fig. 4. These additional cuts reduce the data sample by a factor ~ 40, while retaining about 85% of the signal events. The ratio of the signal yields is computed from the $J/\psi\pi^+\pi^-$ invariant mass spectrum, in the kinematic region in which the $X(3872)$ candidate has $p_T > 8\,\mathrm{GeV}/c$ and $|y| < 2.2$. The resultant mass spectrum, after all the cuts, is shown in fig. 5. The signals of $\psi(2S)$ and $X(3872)$ are clear. To extract the number of candidates, an unbinned log likelihood fit is performed to the invariant mass spectrum of the $J/\psi\pi^+\pi^-$ range from $3.6\,\mathrm{GeV}/c^2$ to $4.0\,\mathrm{GeV}/c^2$, with an average of 2.4 candidates for an accepted event.

The $\psi(2S)$ signal is parametrized using a double Gaussian function, the $X(3872)$ signal is fitted with a single Gaussian. A second-order Čebyšëv polynomial is used for the background.

The statistical error on the number of the $X(3872)$ is about 20%. From the fit, the number of $\psi(2S)$ is 7346 ± 155 and the number of $X(3872)$ is 548 ± 104.

4. – Acceptance and efficiency

The acceptance reflects the finite geometrical coverage of the CMS detector and the limited kinematic of the muon trigger and reconstruction systems. These are constrained by the thickness of the material in front of the muon detectors and by the track curvature in the magnetic field. For example, the acceptance of the J/ψ meson is defined as the fraction of detectable muon $J/\psi \to \mu^+\mu^-$ decays, as a function of the dimuon transverse momentum and rapidity: $A(p_T; y) = \frac{N_{\mathrm{det}}(p_T;y)}{N_{\mathrm{gen}}(p_T;y)}$, where N_{det} is the number of detectable J/ψ events in a given $(p_T; y)$ bin and N_{gen} is the corresponding total number of generated J/ψ events in the simulation [7].

The efficiency is defined as the ratio of the passed events over the total generated events, in the acceptance region.

(2) $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where η is the pseudorapidity and ϕ is the azimuthal angle between the particles.

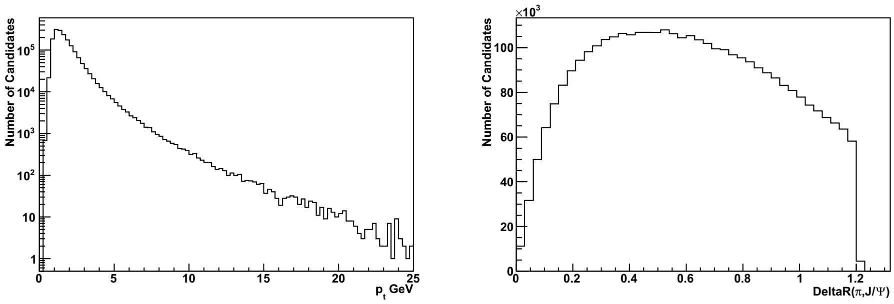

Fig. 4. – Characteristics of the $(\pi^+\pi^-)$ system as measured in data. Left: $p_T(\pi^+\pi^-)$ (where GeV is meant to be GeV/c); right:ΔR between J/ψ and $(\pi^+\pi^-)$.

These definitions can be applied to the $X(3872)$ and $\psi(2S)$, either for the J/ψ and for the pions pair $(\pi^+\pi^-)$. The corrected signal yield can be factorized into four components. $A_{J/\psi}$ and $\epsilon_{J/\psi}$ are the acceptance and the efficiency for the J/ψ reconstruction. Similarly, $A_{\pi\pi}$ and $\epsilon_{\pi\pi}$ are the acceptance and efficiency of the pion pair. The final correction value is

$$C = \frac{A_{J/\psi}(X(3872)) \times \epsilon_{J/\psi}(X(3872)) \times A_{\pi\pi}(X(3872)) \times \epsilon_{\pi\pi}(X(3872))}{A_{J/\psi}(\psi(2S)) \times \epsilon_{J/\psi}(\psi(2S)) \times A_{\pi\pi}(\psi(2S)) \times \epsilon_{\pi\pi}(\psi(2S))}\,. \tag{2}$$

The ratio of each of the four components and their product, due to the similar properties of the particles, is close, but not equal, to unity.

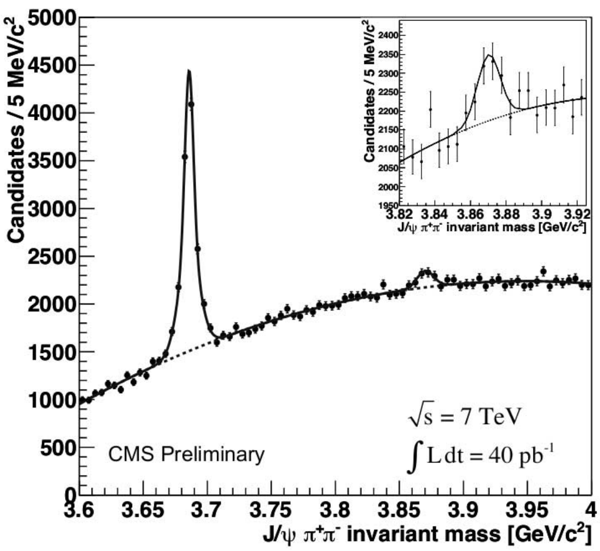

Fig. 5. – $J/\psi\pi^+\pi^-$ invariant mass spectrum in the region where the candidates have $p_T > 8\,\mathrm{GeV}/c$ and $|y| < 2.2$. In the top right there is a blow-up of the $X(3872)$ mass range. The curve represents the unbinned log likelihood fit [1].

For the prompt component: $A_{J/\psi} = 0.876$, $\epsilon_{J/\psi} = 0.842$ (is the efficiency of reconstructing J/ψ) and $A_{\pi\pi} \times \epsilon_{\pi\pi} = 1.098$, the correction factor is: 0.809 ± 0.014(stat.). For the non-prompt component is: 0.990 ± 0.018(stat.). An assumption of the non-prompt component fraction is obtained using a B-enriched sample with a further selection based on $c\tau > 0.1$ mm in the transverse plane.

5. – Result

From the invariant mass distribution fit, the numbers of candidates of $X(3872)$ and $\psi(2S)$ are: $N_{X(3872)} = 548 \pm 104$(stat.) and $N_{\psi(2S)} = 7346 \pm 155$(stat.), respectively. The ratio of "acceptance corrected" yields is

$$(3) \quad R = \frac{N_{X(3872)}}{N_{\psi(2S)}} \times \frac{1}{C} = \frac{\sigma(pp \to X(3872) + \text{anything}) \times \text{BR}(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times \text{BR}(\psi(2S) \to J/\psi\pi^+\pi^-)} .$$

Using the correct value of $C = 0.872$ in the ratio of measured signal yields gives a result of: $R = 0.087 \pm 0.017$(stat.) ± 0.009(syst.) The first error comes from the statistical uncertainty of the signal yield in the data and the second error is the systematic uncertainty [1].

6. – The 2011 data

In 2011 the huge amount of collected data allows to continue the study of the $X(3872)$ particle. The performance of the LHC had increased the acquisition of about 200 times with respect to 2010 data. The total collected data, up to July, is about $\sim 1\,\text{fb}^{-1}$.

The great number of collisions needs an important improvement of the trigger system. In particular for this analysis, there is the addition of new HLT triggers. The principal triggers used are the *HLT_Dimuon7_Jpsi_X_Barrel_v1/3* and *HLT_Dimuon6p5_Jpsi_Barrel_v1*. They require that $p_T^{\mu\mu} > (6.5)7\,\text{GeV}/c$, respectively, and that the event lies in the barrel region ($|\eta| < 1.2$).

At the trigger level the transverse momentum of the J/ψ has to be greater than $7\,\text{GeV}/c$, must lie in the rapidity region $|y| < 1.25$ and the candidate has to stay in the mass window of $2.95\,\text{GeV}/c^2 < m < 3.25\,\text{GeV}/c^2$. The muons are accepted if they are in a particular acceptance region: $p_T > 4\,\text{GeV}/c$ for $|\eta| < 1.3$ and $p_T > 3.3\,\text{GeV}/c$ for $1.3 < |\eta| < 2.4$. The probability vertex of the dimuon system is required to be greater than 1%. The J/ψ candidates are kept if they lie in the mass window $3.019\,\text{GeV}/c^2 < m_{J/\psi} < 3.167\,\text{GeV}/c^2$. The tracks selection has been modified a little: the minimum transverse momentum is $p_T > 0.6\,\text{GeV}/c$ and the ΔR between the J/ψ and both pions has to be smaller than 0.7. The $X(3872)$ candidate is required to be in a specific rapidity region ($|y| < 1.25$) and to have a higher transverse momentum ($p_T > 9\,\text{GeV}/c$). The four-vertex probability has to be greater than 1%, as in the 2010 selection.

The resultant invariant mass spectrum is shown in fig. 6. The fitting is made using a Voigtian function for the $\psi(2S)$ peak and a Gaussian function for the $X(3872)$, the background is fitted with a Čebyšëv polynomial. From the fit, the number of $X(3872)$ is 5303 ± 341 and the number of $\psi(2S)$ is 72594 ± 518.

Further information can be found in [8] and [9].

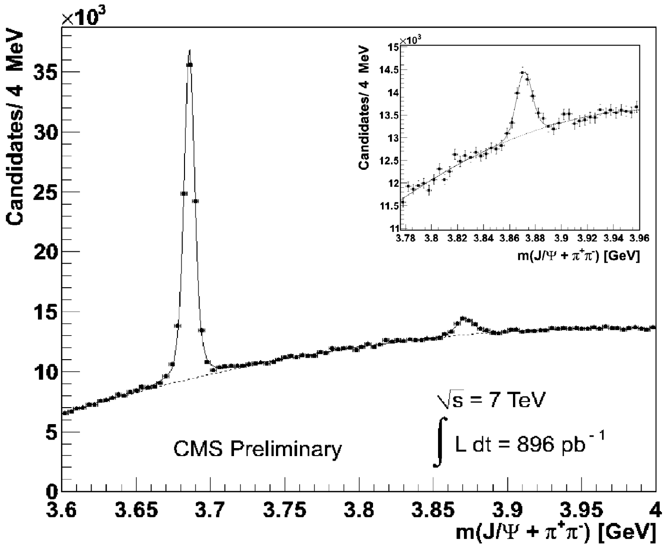

Fig. 6. – Invariant mass spectrum of the 2011 data, $\sim 900\,\mathrm{pb}^{-1}$. In the top right a blow-up of the $X(3872)$ mass range is shown [9].

7. – Conclusion

This work has presented a measurement of the $X(3872)$ particle production in pp collisions at $\sqrt{(s)} = 7\,\mathrm{TeV}$ in the CMS experiment, in the decay mode into a J/ψ and a pions pair.

The measurement is being performed with the $\sim 40\,\mathrm{pb}^{-1}$ collected in 2010, and the cross section has been measured relative to the production of $\psi(2S)$ decaying into the same final state, in such a way factorizing most of the uncertainties. The accuracy is limited to about 20% due to the statistical error, while the systematics is $\sim 10\%$. About 500 events are reconstructed in 2010.

The larger dataset collected by CMS up to July 2011 ($\sim 1\,\mathrm{fb}^{-1}$) has allowed a much better statistical evidence of such a decay, while the systematic uncertainties are still under evaluation. Where possible, data-driven methods are used to validate the analysis, especially in the pion tracking efficiency.

A first look at the 2011 data is also shown. The amount of data collected will permit a continuation of the analysis. Further studies would investigate the fraction of the prompt component and the nature of the $X(3872)$.

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