CMS quarkonium Production at 13 TeV

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Abstract. A wide range of studies of quarkonium production and spectroscopy are performed by the CMS experiment. The quarkonium system is interesting and can be used mainly to probe the underlying Quantum Chromo Dynamics (QCD) processes but also to tune MC generators at new energies, since heavy flavour (HF) states are background to many searches, and can be used to obtain calibration and understanding of the detectors. Events are selected from muon pairs, and the final state includes hadrons and photons. The identification of secondary vertices allows for the separation of prompt (P) and non prompt (NP) production.

In the conference talk I presented the many recent results obtained with 13 TeV data at the Large Hadron Collider (LHC) but in this paper I focus on the most recent result: the first observation of resolved $b_1(3P)$ and $b_2(3P)$ states and their mass splitting measurement through the decay channel $b_1(3P) \rightarrow \tau(3S)\gamma$.

1. Introduction
The LHC at CERN is the highest energy accelerator in the world and is one of the largest and truly global scientific projects ever. It includes four interaction points, two of which are housing the ATLAS and CMS general purpose detectors, designed to search for the Higgs Boson. The CMS experiment has produced many results on quarkonium production and spectroscopy.

The quarkonium system can be used as an excellent test of perturbative and non perturbative QCD and data at 13 TeV is used to verify Non Relativistic QCD (NRQCD) and effective field theory predictions at this new energy regime.

2. The CMS detector
CMS (Compact Muon Solenoid) [1] is a classical collider detector, taking proton proton collisions data at LHC at $\sqrt{s} = 13$ TeV since 2015.

During the recent down (LS1) various subsystems have been upgraded. The main challenge has been to mitigate the effects of radiation on the performance of the silicon sensors of the tracker and has been addressed by equipping it to operate at lower temperatures (down to -20°C). Also the muon system has been improved and a fourth measuring station added to each muon endcap, in order to maintain the discrimination between low transverse momentum ($p_T$) muons and background as the LHC beam intensities increase. In Figure 1 shows schematically the stand-alone reconstruction capability by muon detectors. We use a tracker-muon reconstruction match: inside-out, more efficient at low $p_T$ and outside-in, more efficient at high $p_T$.

CMS experiment has an excellent dimuon mass resolution. In Figure 2 exhibits a plot of the whole vector resonance spectrum as a function of the $\mu^+\mu^-$ invariant mass. quarkonium is reconstructed through dimuon triggers and dimuon final states. The three LHC experiments,
ATLAS, CMS and LHCb, complement each other in measuring HF properties. While LHCb is a dedicated HF experiment, specific topic/channels where ATLAS and CMS can be competitive must be accurately selected already at trigger level, since the trigger has a limited bandwidth. Over time, triggers are tightened to balance higher rate from increasing luminosity and this can affect quarkonia data sample. High $p_T$ is only accessible in ATLAS/CMS, while low $p_T$ dimuon trigger is the high priority in LHCb and must be kept at reasonable rate in ATLAS/CMS. We use dedicated triggers for $J/\psi$, $\Upsilon$, $B_S(\mu\mu)$ data samples. CMS has published over 15 onia–related papers: a very good dimuon mass resolution (depending on rapidity), a secondary vertex resolution of 25 $\mu$m, and high muon detection and identification capabilities made this possible.

3. The quarkonium production theoretical framework

From a naive point of view quarkonium is a simple state: a flavorless meson whose constituents are a quark and its own antiquark, in a bound state. Quarkonia are probes of hadron formation, but production is not yet totally understood and there is a long history of disagreement between theory and experimental results. No theory has simultaneously explained experimental measurements of both production cross-section and polarization. Although Quantum ChromoDynamics (QCD) is well established as the theory of the strong interaction, a complete understanding of the (non-perturbative) processes that lead to the binding of quarks and gluons into hadrons is still lacking [2].

Some popular models on the market are the colour singlet model (CSM) and the colour octet mechanism (COM/NRQCD). CSM production model for quarkonia may require a quark-antiquark state ($q\bar{q}$) produced as colour-singlet, a colour neutral object, while COM may ask a quark-quark pair being produced in any colour, subsequently reaching a colour singlet state by the emission radiation of soft gluons (see the schematic diagrams in Figure 3 and 4).

More data is needed to study the process and LHC provides luminosity, higher energy scale, extended cross-section and high $p_T$ range.

Most models stand for direct production only but experiments cannot completely separate direct production, or cannot separate all the time the direct production.

Charmonium production occurs at LHC through two distinct mechanisms and with comparable contributions: a) prompt (P), direct production in the pp interaction, experimental
Figure 3. (colour online) LO diagram of a $q\bar{q}$ pair as a color singlet neutral object (plot by P. Faccioli).

Figure 4. (colour online) A coloured octet object subsequently reaching a color singlet state by the emission of soft gluons (plot by P. Faccioli).

distinguishable due to the absence of a long pseudo-proper-time tail; b) non-prompt (NP), through feed-down from decays of heavier quarkonium states and $b$-hadrons, with long pseudo-proper-time tail due to the long lifetime of $b$-hadron. See schematic pictures in Figure 5.

Figure 5. (colour online) Schematic prompt (P) and non-prompt (NP) production.

Figure 6. (colour online) Projections on the $\mu\mu$ invariant mass (left) and pseudo-proper-decay-length (right) axes, for $J/\psi$ (top) and $\psi(2S)$ (bottom) events.

To measure prompt and non-prompt yield fractions simultaneously and disentangle the two contributions CMS exploits an unbinned fit to 2D dimuon mass and pseudo-proper time. Figure 6 shows the projections on the dimuon invariant mass (left) and pseudo-proper-decay-length $ct$ (right) axes, for the $J/\psi$ (top) and $\psi(2S)$ (bottom) events at 13 TeV. The right panels show dimuons of invariant mass, and event selection is within $\pm 3\sigma$ of the pole masses. The curves, identified in the legends, represent the result of the fits. The vertical bars on the data points show the statistical uncertainties. The mass signal is modeled using Crystal Ball functions. The $ct$ background also has P and NP components.

Nowadays one of the most accredited theories is NRQCD, that treats heavy quarkonia ($cc, bb$) as a Non-Relativistic systems. It is an effective theory that factorises the production mechanism in two distinct phases: the production of $q\bar{q}$ in the regime of perturbative QCD, calculating short
distance coefficients (SDCs) and a non-perturbative long distance matrix elements (LDME). The missing contribution are thought to derive from $q\bar{q}$ pairs created in an intermediate colour octet state, that evolve into a color singlet state physical state by nonperturbative emission of soft gluons. LDMEs, thought to be universal, have to be extracted from data, although expected to obey scaling rules.

The double differential cross section is calculated from CMS production yields data, in bins of rapidity $y$ and transverse momentum $p_T$, for charmonium and bottomonium S-wave resonances [3] and compared to data taken at lower energies. These results show similar scaling for bottomonium and charmonium S-wave states, contributing to consolidate the underlying hypothesis of NRQCD and to provide further input to constrain the theory parameters. These measurements should reduce theoretical uncertainties from the extraction of LDMEs.

4. The Mass splitting of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states of quarkonium

Given the high luminosity yields at LHC one can explore new observables and the excellent dimuon mass and photon energy resolution of CMS allows to study P-wave quarkonium states through their radiative decays.

The bottomonium family ($b\bar{b}$) plays a special role in understanding how the strong force binds quarks because, due to the high b-quark mass, it allows important theoretical simplifications. The measurements of the masses of the $\chi_b(3P)$ triplet states, with total angular momentum $J = 0, 1, 2$, is particularly interesting to probe details of the $b\bar{b}$ interaction and test theoretical treatments of the influence of open beauty states on the bottomonium spectrum.

The $\chi_b(3P)$ triplet state, first discovered at a mass of about 10.5 GeV by ATLAS [4], is interesting given that its properties could be affected by the proximity of the open-beauty ($BB$) threshold.

A new result from the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states and their masses has been obtained by CMS through the decay channel $\chi_b(3P) \rightarrow \Upsilon(3S)\gamma$ [5].

The $\Upsilon(3S) \rightarrow \mu^+\mu^-$ decay trigger requires a $\mu^+\mu^-$ pair with two opposite sign muons coming from a common vertex. The background level in the $\Upsilon(3S)\gamma$ mass distribution is reduced by selecting a high purity $\mu^+\mu^-$ pairs with invariant mass within a few sigma from the nominal world-average mass $M_{\Upsilon(3S)}=10.3552$ GeV [7].

For improved energy resolution we identify the photons produced in the $\chi_b(3P) \rightarrow \Upsilon(3S)\gamma$ radiative decays through their conversions to $e^+e^-$ pairs inside the CMS beampipe and/or tracker [6]. To accurately measure the invariant mass of the $\chi_b(3P)$ candidate, the photon energy scale (PES) must be calibrated and this is done using $\chi_{c1} \rightarrow J/\psi \gamma \rightarrow \mu^+\mu^-\gamma$ events. The fitted result is then used for the event-by-event correction of the photon energy entering in the computation of the $\Upsilon(3S)\gamma$ invariant mass.

Figure 7 shows the invariant mass distributions of the $\chi_{b1}(3P) \rightarrow \Upsilon(nS)\gamma$ candidates ($n = 1, 2, 3$), after PES correction. The inset shows the $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$ masses fitted before (open squares) and after (filled circles) the PES correction, with vertical error bars representing the statistical uncertainties. The world-average mass values [7] are shown by the horizontal bands, with dashed lines representing their total uncertainties. The $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ events are selected with the same criteria as used for the $\Upsilon(3S)$ gamma events, except that the dimuon invariant mass is required to be a few $\sigma$ from the mass of $\Upsilon(1S)$ and $\Upsilon(2S)$ respectively.

The clear $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$ peaks seen in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ distributions in Figure 7 are fitted and the resulting $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$ masses are in agreement with the world-average values [7], as shown in the inset, confirming the validity of the PES correction function. The $J=1$ and $J=2$ states are well resolved thanks to a mass resolution around 2.2 MeV.

Figure 8 compares the measured $\Upsilon(3S)\gamma$ invariant mass distribution with the result of an unbinned extended maximum-likelihood fit to the superposition of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ signal peaks plus a smooth underlying background resulting from uncorrelated dimuon-photon
pairs. Each of the two signal peaks is described by a double sided Crystal Ball function. For the details on the fitting procedure and parameters see reference [5]. The fit $\chi^2$ is 46 for 57 degree of freedom and 372 ± 36 signal events.

In summary, data samples collected by CMS in pp collisions at 13 TeV, in the years 2015, 2016 and 2017, were used to measure the invariant mass distribution of the $b(3P) \to \Upsilon(nS)\gamma$ candidates, with the $\Upsilon(3S)$ detected in the dimuon decay channel and the photon reconstructed through conversions to $e^+e^-$ pairs. The measured distribution is well reproduced by the superposition of the $b_1(3P)$ and $b_2(3P)$ quarkonium states, on the top of a smooth underlying continuum due to uncorrelated dimuon-photon combinations.

This is the first time that the $J = 1$ and 2 states are well resolved and their masses individually measured [5] : $M(b_1(3P)) = 10,513.42 \pm 0.41(stat) \pm 0.18(syst)$ MeV and $M(b_2(3P)) = 10,524.02 \pm 0.57(stat) \pm 0.18(syst)$ MeV and they are determined with respect to the world-average value of the $\Upsilon(3S)$ mass, which has an uncertainty of 0.5 MeV. The mass splitting is measured to be $\Delta M = 10.60 \pm 0.64(stat)$ MeV, where the statistical uncertainty takes into account the correlation between the two fitted mass values.

This is the first measurement of the mass splitting of the $b(3P)$ resonance doublet structure. The mass difference between the $J=1$ and 2 states is significantly larger than mass resolution ($\approx 2$ MeV) and this supports the standard mass hierarchy.

This measurement fills a gap in the spin-dependent bottomonium spectrum below the open beauty threshold and should significantly contribute to an improved understanding of the nonperturbative spin-orbit interactions affecting quarkonium spectroscopy.

References
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