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Quarkonium physics in CMS

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Abstract

The CMS experiment is collecting and processing LHC collision data. In the first few months of LHC operation, considerable emphasis is being placed on quarkonium measurements, profiting from affordable dimuon trigger rates, even with relatively loose trigger paths. The performance capability of CMS for understanding quarkonium physics in the dimuon decay channel will be illustrated with Monte Carlo studies and, hopefully, with some preliminary measurements of dimuon mass distributions in the J/ψ and Upsilon mass windows, from pp interactions at 7 TeV.

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Quarkonium physics in CMS

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The CMS experiment is collecting and analyzing collision data from LHC. In the first few months of LHC operation, the CMS experiment has placed considerable emphasis on quarkonium measurements, profiting from affordable dimuon trigger rates, even with relatively loose trigger requirements. Some preliminary results will show the performance capability of CMS for investigating quarkonium physics in the dimuon channel, particularly in the J/ψ and Υ mass windows, from pp interactions at $\sqrt{s} = 7\text{TeV}$.

1. Introduction

For more than 30 years after its discovery, the production mechanism of prompt quarkonium in hadronic collisions has remained rather puzzling. Several theoretical models have been formulated [1], [2], [3] in the attempt to reproduce the experimental J/ψ and Υ data, measured at both fixed-target and collider experiments. The Colour-Singlet Model (CSM), including leading and next-to-leading order corrections [2], the Colour-Evaporation Model (CEM) [4], the Colour-Octet Model (COM) [5], Non-Relativistic QCD (NRQCD) [6] and the Soft Colour Interaction (SCI) model all fail to describe simultaneously the quarkonium cross sections [3], [7], [8] and the polarization measurements [9], [10], [11], obtained at the Tevatron by CDF and D0.

Furthermore, quarkonium polarization measurements performed at CDF and D0 are not in complete agreement, indicating that efficiencies are perhaps not completely understood and systematics are not fully controlled. What appears to be clear is that the measurement of the full set of observables (both polar and azimuthal anisotropies), in all polarization reference frames, performed on high statistics data samples is of crucial importance for a complete understanding of the underlying production process.

A new opportunity is offered by the LHC, though its main impact will be on the search for new physics. At LHC, theoretical predictions will

be tested at a much higher energy and in a wider rapidity range compared to the past. J/ψ and Υ cross sections will be probed beyond $p_T=20\text{ GeV}/c$ for the first time.

The Compact Muon Solenoid (CMS) Collaboration has strongly focused its early physics programme on high statistics measurements of quarkonia cross sections and polarizations in pp collisions at 7TeV centre-of-mass energy.

In this paper, we will show the capabilities of CMS to record high statistics quarkonia samples in the dimuon decay channel and will illustrate the full analysis workflow for cross section and polarization measurements. Finally, we will present early evidence for quarkonia signatures in the dimuon invariant mass spectrum from the first sample of recorded data.

2. J/ψ , Υ production at hadron colliders

In hadronic interaction J/ψ and Υ can be produced directly (*prompt*), indirectly (*prompt – indirect*), from the decay of heavier quarkonia states (χ_c , ψ' , χ_b), or from b-hadron decay (*non – prompt*). The latter, have distinctive features compared to *prompt* because of the displaced point of production (the b-lifetime decay path). *Non – prompt* J/ψ production can be directly related to b-hadron production via the well measured $\text{BR}(b \rightarrow J/\psi)$, leading to a direct measurement of $b\bar{b}$ cross-section in pp collisions.

The CMS apparatus exploits the excellent tracking performance and redundancy of its Muon system to detect dimuon pairs from quarko-

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nia decay. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracking detectors, which provide accurate determination of the track momenta, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muon trajectories are measured in gas-ionization detectors embedded in the steel return yoke. A more detailed description of CMS can be found elsewhere [12]

Muons are measured in the pseudorapidity region $|\eta| < 2.4$, with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5 %, for p_T values up to 1 TeV/c.

The acceptance in the forward $|\eta| > 1.0$ region allows detection of all muons down to the lowest p_T (~ 2 GeV/c) whereas in the central $|\eta| < 1.0$ region an acceptance cut of $p_T > 4$ GeV/c is imposed by the apparatus design and magnetic field. Due to these features, several High Level Trigger (HLT) paths have been designed to maximize the signal yields and the phase space coverage down to the lowest muon p_T , thus improving the accuracy on the polarization measurement. During the machine startup phase, when LHC was delivering luminosity below $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, a minimum bias trigger condition has been applied at the lowest (L1) trigger level. This trigger requirement has been used to collect the data sample used for the present analysis. The HLT conditions have been applied to streaming the events for offline analysis and not as active online event filtering.

3. Muon reconstruction in CMS

Tracks reconstructed in the inner silicon and pixel trackers, also referred to as Tracker Tracks (TT), which are associated to tracks, or track-segments, independently reconstructed in the Muon system, are generally considered muon candidates. In the first case (TT matched to a fully reconstructed Standalone track in the Muon sys-

Figure 1. Global muon data-MC comparison from 7TeV collisions using a minimum bias trigger. Points with error bars: data; filled histograms: Monte Carlo (red: muons from light-hadron decay; blue: muons from heavy-flavour; black: hadron punch-through; green: fake muons)

tem), a global re-fit of the tracker and Muon system hits is performed to yield a high purity and quality Global Muon (GM). In the second case (TT matched to at least one track segment detected in the Muon system), the reconstruction in the silicon and pixel tracker defines the track parameters, and the Muon system is used mainly to confirm and identify the track as a muon. The latter type are referred to as Tracker Muons (TM), and their quality is in general poorer than that of GM. The tracker-muon algorithm however achieves a better reconstruction efficiency at low- p_T compared to the global-muon, since at low- p_T fewer hits in the muon stations may be available for a Standalone muon, hence a Global Muon, to

be reconstructed. The two muon categories are not mutually exclusive, there is an overlap between the reconstruction algorithms. However, there are criteria imposed at the analysis level to make the two categories exclusive. Independently of the category, the muon momentum is determined by the fit in the inner tracker system (TT momentum).

In $\sqrt{s} = 7$ TeV collisions and luminosity below $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, the spectrum of low- p_T particles reaching the Muon system is dominated by light-hadron decay muons ($\sim 73\%$), whereas prompt muons, mostly from heavy flavour decay, account for the rest ($\sim 25\%$). There are additional contributions from hadron punch-through and mistagged tracks (fake muons). Fig. 1 compares the pseudorapidity and p_T distribution of reconstructed Global Muons from minimum bias data to a sample of GEANT4 simulated events, subdivided into the different contributions. Large acceptance is achieved in the forward pseudorapidity region because of the less stringent requirements on the track p_T . The simulation appears to reproduce the data extremely well.

4. Dimuon event selection

The present data sample corresponds to the first 15 nb^{-1} of integrated luminosity recorded by CMS using a minimum bias trigger. Events which satisfy the HLT requirements for the dimuon, or single muon with $p_T > 3 \text{ GeV}/c$, paths are considered for further analysis.

Oppositely charged global-global or global-tracker muon pairs have been selected by applying tight criteria to reject the fake muon background and enhance the track and vertex qualities. The global-tracker combination is used to achieve high efficiency on the rather soft muons from quarkonia decay at the expense of a somewhat larger background. In addition, a fit requiring the two muons to come from a common vertex is applied and only events with a χ^2 probability larger than 0.1% are retained.

Fig. 2 shows the dimuon invariant mass spectrum in the J/ψ region (points with error bars). The signal yield and the resonance parameters have been extracted via a maximum log-

Figure 2. Dimuon invariant mass at $\sqrt{s} = 7$ TeV from 15 nb^{-1} integrated luminosity. Data are shown as points with error bars. The black curve represents the results of the global fit, whereas the blue curve shows the background contribution only.

likelihood fit performed in the invariant mass range from 2.6 to 3.5 GeV/c^2 . The fitting function is the convolution of a Crystal Ball function for the signal, which takes into account the detector resolution and the radiative (low mass) tail from internal bremsstrahlung, and an exponential to describe the background.

Table 1

J/ψ event yield and mass parameters.

Mass (GeV/c^2)	σ (MeV/c^2)	signal
3.092 ± 0.001	42.7 ± 1.7	1230 ± 47

The parameters of the exponential background have been fixed to the values obtained from a fit to the mass sidebands. The results of the fit are reported in Tab. 1, and the fitting function is superimposed to the data in Fig. 2. The data are not corrected for the bias on the momentum measurement, which is responsible for the shift and broadening of the reconstructed mass peak.

Due to the limited statistics only small hints of the $\Upsilon(nS)$ states are observed in the dimuon mass range above 9 GeV/c^2 . However, a few thousands fully reconstructed $\Upsilon(nS)$ are already expected with an integrated luminosity of $\sim 1 \text{ pb}^{-1}$,

as shown in Fig. 3, from a simulation of the yield of $\Upsilon(nS)$ at $\sqrt{s} = 7$ TeV.

Figure 3. Predicted yield of $\Upsilon(nS)$ resonances at $\sqrt{s} = 7$ TeV after 1pb^{-1} integrated luminosity. Results are from a Monte Carlo simulation.

5. Towards inclusive cross section measurements

In order to perform a measurement of the inclusive J/ψ differential cross section times its branching ratio into two muons the number of observed signal events, in a given p_T bin, has to be corrected for the detector acceptance and the muon efficiency. The corrected yield must then be normalized to the integrated luminosity in each p_T bin, and to the bin size.

The J/ψ acceptance is determined by the kinematics of the decay-muons across the full p_T and pseudorapidity space. This is obtained by simulating J/ψ to dimuon events and by using the generated values directly. The muon acceptance strongly depends on the amount of traversed material before reaching the Muon system, and the B-field curvature, which naturally impose different p_T thresholds in different η regions. Additional criteria on the muon p and p_T are applied in order to obtain an acceptance efficiency uniformly above 10% across the whole pseudorapidity coverage. Furthermore, muons from *prompt*

and *non-prompt* J/ψ s have different acceptance maps, because the polarization gives distinctive features to the muon momentum spectrum. This feature should be taken into account in a fully inclusive measurement.

The J/ψ efficiency is obtained by factorizing the single-muon detection efficiencies and the vertex efficiency, and by considering any residual correlation term. The single-muon efficiency is determined directly from the data using the tag-and-probe (T&P) method. The correlation factor is obtained from Monte Carlo. Several terms contribute to the single-muon efficiency: the trigger, the tracking identification and the reconstruction efficiencies. The first two have a strong dependence on p_T , the latter is independent of p_T and varies little with η .

The present statistics would only allow to calculate the J/ψ inclusive cross section in wide p_T and rapidity bins. Thus, large statistics and systematic uncertainties, mostly related to the binning and the T&P method accuracy, would affect the measurement precision. From a simulation using the equivalent of $\sim 150\text{nb}^{-1}$ of recorded integrated luminosity, CMS expects a $\sim 20\%$ precision on the J/ψ differential cross section, in each p_T and y bin.

Inclusive Υ cross section will be measured by CMS in a similar manner. Here, however, the task is simplified by the absence of a *non-prompt* contribution to the Υ yield.

6. Distinguishing *prompt* and *non-prompt* J/ψ

The *prompt* J/ψ differential cross section and polarization can be calculated after subtraction of the *non-prompt* contribution coming from b-hadron decay. J/ψ from b-hadron decays are likely to be displaced with respect to the primary vertex by the b-hadron lifetime ($\sim 1.5\text{ps}$). The extraction of the *non-prompt* J/ψ component is done by a simultaneous maximum-likelihood fit of the dimuon invariant mass and the pseudo-proper decay length, defined as:

$$l_{xy}^{J/\psi} = \frac{L_{xy}^{J/\psi} \cdot M^{J/\psi}}{p_T^{J/\psi}} \quad (1)$$

where $L_{xy}^{J/\psi}$ is the component of the decay length along the J/ψ transverse momentum direction, and $M^{J/\psi}$ and $p_T^{J/\psi}$ are the dimuon mass and transverse momentum, respectively. The pseudo-proper decay length for the *prompt* component can be described by the convolution of a delta function with a vertex resolution function, since l_{xy} should exactly vanish for prompt events in the limit of an ideal detector. The decay length resolution function is obtained, in first approximation, from Monte Carlo. Alternatively, it could be constructed from a more realistic, data driven, resolution model, by using an event-by-event full vertex covariance error matrix.

Figure 4. The $l_{xy}^{J/\psi}$ distribution for *prompt* and *non-prompt* simulated J/ψ events at $\sqrt{s} = 14$ TeV (points with error bars), and the results of the likelihood fit in the 9-10 GeV/c p_T region.

For the *non-prompt* component the convolution of a b-lifetime exponential function with the same resolution function is used. An additional gaussian smearing function is added to take into account the difference between the pseudo-proper ($\propto M^{J/\psi}/p_T^{J/\psi}$) and proper ($\propto M^B/p_T^B$) decay length definition.

Finally, the pseudo-proper decay length functional form describing the background is obtained from data, by a fit to the J/ψ mass sidebands, and

Figure 5. Fraction of *non-prompt* J/ψ from b-hadron decay (histogram) as a function of p_T from Monte Carlo simulated *prompt* and *non-prompt* J/ψ events at $\sqrt{s} = 14$ TeV, and the results of the likelihood fit (points with error bars).

convoluted with the detector resolution function.

Fig. 4 shows the distribution of $l_{xy}^{J/\psi}$, for J/ψ with p_T between 9 and 10 GeV/c, and the likelihood fit results for a sample of Monte Carlo simulated *prompt*, *non-prompt* J/ψ and non-resonant background events, at the centre-of-mass energy of 14 TeV. The long exponential tail represents the contribution from b-hadron decay. Fig. 5 shows the overall p_T dependence of the *non-prompt* J/ψ component and the likelihood fit result.

Several systematic errors could affect the measurement of the *prompt* J/ψ fraction. Alternative vertex resolution and the b-hadron lifetime models should be exploited and compared to the Monte Carlo-based approaches. Different descriptions of the background may provide a better understanding the level of uncertainty. The effect of any possible residual detector misalignments on the mass and lifetime fits should be understood and quantified.

7. Quarkonia polarization

CMS plans to perform a measurement of the *prompt* J/ψ and Υ polarizations in the full p_T

and rapidity region. The three anisotropy coefficients ($\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$) of the decay angular distribution will be measured in all polarization frames (helicity and Collins-Soper) through a fit of the $\cos\theta$ vs ϕ distribution, where θ and ϕ refer to the positive decay-muon [9].

To measure the Υ polarization, a simultaneous maximum-likelihood fit of the dimuon invariant mass in the Υ region and the positive muon $\cos\theta$ and ϕ angular distribution is performed. The functional form for the signal is obtained from Monte Carlo, as well as the angular acceptance and efficiency maps, whereas the background is described using the data mass-sidebands. The availability of a larger data sample will allow to perform important cross checks of the Monte Carlo derived functional forms using data-driven methods (T&P).

The determination of the *prompt* J/ψ polarization is more complex, because of the additional *non-prompt* contribution. In the previous section, we have shown how a simultaneous fit of the invariant mass and pseudo-proper decay length yields a measurements of the *non-prompt* J/ψ fraction. An extension of this method provides a way to determine the polarization parameters as a function of the J/ψ p_T and rapidity. For each dimuon event, one can define a more general likelihood function $L(m_{\mu\mu}, l^{J/\psi}, \cos\theta, \phi)$, which depends on the dimuon mass, the pseudo-proper decay length, and the positive muon $\cos\theta$ and ϕ . The likelihood is constructed as the sum of three contributions: the *prompt* signal, the *non-prompt* signal and the background. Monte Carlo and data-driven functional forms are used to parameterize the different terms entering the likelihood definition. By performing preliminary partial fits, one is able to constraint some of the parameters and allow the final fit to have only a limited number of free parameters, namely the six polarization coefficients for the *prompt* and *non-prompt* J/ψ components.

8. Conclusion and outlook

Early physics signature at CMS provide an excellent opportunity to analyze the overall performance of the experimental apparatus and to

study detector alignment and perform accurate detector calibrations. They are also useful as benchmarks of several analyses workflows, to tune the analysis algorithms, and to establish the sensitivity to specific physics signatures. The physics of quarkonia offers all of that and, in addition, the possibility to investigate the controversial issue of its production mechanism in an unexplored kinematic domain.

CMS will have in the next months the opportunity to contribute significantly to this field, profiting from the excellent performance of the detector and the improving capability of the LHC to deliver higher luminosities.

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