Quarkonium and heavy flavour production in Run I and first results with 13 TeV data at CMS

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This work presents results on quarkonium and heavy flavour production using data collected by the CMS experiment at the LHC in pp collisions during Run I. The emphasis is placed on the most recent measurements, including the S-wave cross sections up to transverse momenta exceeding 100 GeV, the polarizations of Υ(nS) mesons as function of charged particle multiplicity, as well as the study of B_c^+ mesons decaying to $J/\psi\pi^+$ and $J/\psi\pi^+\pi^+\pi^-$. Moreover, preliminary dimuon mass distributions obtained with early Run II data collected at $\sqrt{s} = 13$ TeV in 2015 are shown.

The European Physical Society Conference on High Energy Physics
22-29 July 2015
Vienna, Austria

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The CMS detector at the Large Hadron Collider (LHC) took proton-proton (pp) collision data at a center-of-mass energy, $\sqrt{s}$, of 7 TeV in 2010 and 2011. Total integrated luminosities of about 37 pb^{-1} and 5 fb^{-1} were collected, respectively. In 2012, the center-of-mass energy was raised to 8 TeV, at which about 21 fb^{-1} of data were collected. In 2013 and 2014, the accelerator complex at CERN was shutdown for consolidation and upgrade work. Early 2015, the LHC restarted at $\sqrt{s} = 13$ TeV. Up to the EPS conference, 61.8 pb^{-1} of data were collected with a magnetic field of 3.8 T.

Numerous results on quarkonium and heavy flavour production based on Run I data were published by the CMS collaboration [1]. Only the most recent measurements are discussed here: the ψ(nS) (n = 1, 2) and Υ(nS) (n = 1, 2, 3) production cross sections [2, 3], the polarizations of Υ(nS) mesons as function of charged particle multiplicity [4], and the measurement of the ratio $(B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-) / (B_c^+ \rightarrow J/\psi \pi^+)$ and the production cross sections times branching fractions of $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ [5]. These results use the dimuon data sample collected in pp collisions in 2011.

Moreover, preliminary dimuon mass distributions obtained with the early Run II data at $\sqrt{s} = 13$ TeV are presented.

1. Quarkonium production in Run I

CMS measured the cross sections and polarizations of the prompt ψ(nS) and Υ(nS) states as function of transverse momentum, p_T, and rapidity, $|y|$. The double-differential cross sections $\frac{d\sigma}{dp_T d|y|}$ times dimuon branching ratios $\mathscr{B}$ are calculated as

$$\frac{d\sigma(pp \rightarrow \mathscr{Q})}{dp_T d|y|} \times \mathscr{B}(\mathscr{Q} \rightarrow \mu^+ \mu^-) = \frac{N_{\mathscr{Q}}^{fit}(p_T, |y|)}{\mathscr{L}_{int} \cdot \Delta p_T \cdot \Delta |y| \cdot \varepsilon(p_T, |y|) \cdot \mathscr{A}(p_T, |y|)}, \qquad (1.1)$$

where $N_{\mathscr{Q}}^{fit}(p_T)$ is the number of quarkonium events in a given p_T and $|y|$ bin of width Δp_T and $\Delta |y|$, $\mathscr{L}_{int}$ represents the integrated luminosity, $\varepsilon(p_T, |y|)$ denotes the efficiency of trigger, reconstruction and analysis selections, and $\mathscr{A}(p_T, |y|)$ the acceptance. The acceptance depends on the quarkonium polarization which is reflected in the angular distribution of the quarkonium decaying to leptons (here muons),

$$W(\cos \vartheta, \varphi | \vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi), \qquad (1.2)$$

where $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ represents the frame-dependent polarization parameters and ϑ and φ are the polar and azimuthal angles of the positive muon with respect to the z-axis of the chosen reference frame [6, 7]. Commonly used frames are the center-of-mass helicity frame (HX) coinciding with the direction of the quarkonium momentum, the Collins-Soper frame [8] and the perpendicular helicity frame [9].

The acceptance correction was calculated for four different polarization scenarios:

- $\lambda_\vartheta^{HX} = \lambda_\varphi^{HX} = \lambda_{\vartheta\varphi}^{HX} = 0$;

- $\lambda_\vartheta^{HX} = \pm 1$, $\lambda_\varphi^{HX} = \lambda_{\vartheta\varphi}^{HX} = 0$; and

- a data-inspired scenario using $\lambda_\vartheta^{HX} = +0.1(+0.03)$, $\lambda_\varphi^{HX} = \lambda_{\vartheta\varphi}^{HX} = 0$ for the J/ψ (ψ(2S)) based on the average polarization values measured in Ref. [10] and interpolated polarization values measured in Ref. [11] in case of the Υ(nS) states. As quarkonia are seen to be produced essentially unpolarized, the acceptance calculated with the polarization values observed in data is very close to the one using isotropic decays.

The cross sections are determined for quarkonia with $|y| < 1.2$, in various bins of $|y|$, and for a p_T range between 10 and 100 GeV (120 GeV in case of the J/ψ). These measurements therefore tremendously extend the p_T reach of previous cross sections published by CMS [12, 13].

The polarizations of Υ(nS) mesons have not only been measured as a function of p_T and $|y|$, but also as function of charged particle multiplicity, N_{ch}, using Eqn. 1.2. The charged particle multiplicity is defined as the sum of "high purity" tracks [14] with $p_T > 500$ MeV weighted by the likelihood that the track belongs to the primary vertex, excluding the two muons of the quarkonium. Identical to the previous CMS polarization measurements, the three frame-dependent parameters, depicted for the HX frame in Fig. 1, and the frame-invariant quantity $\tilde{\lambda}$ are determined in the HX, CS and PX frames. No strong dependencies of the polarization on N_{ch} was observed, excluding any significant changes in the production process between low and high multiplicity pp collisions.
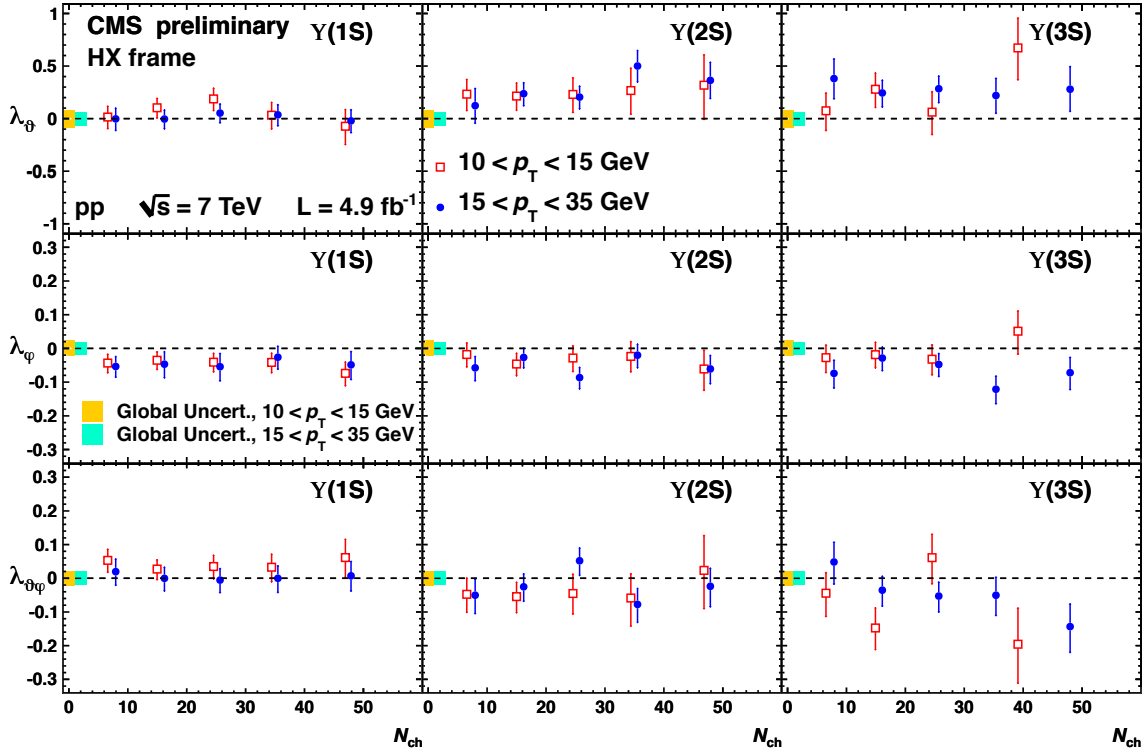

Figure 1: Frame-dependent parameters λ_ϑ (top), λ_φ (middle) and $\lambda_{\vartheta\varphi}$ (bottom) for the Υ(1S) (left), Υ(2S) (middle) and Υ(3S) (right) as a function of charge particle multiplicity, N_{ch}, for $10 < p_T < 15$ GeV and $15 < p_T < 35$ GeV in the HX frame. The error bars represent total uncertainties at the 68.3% confidence level (CL) [4].
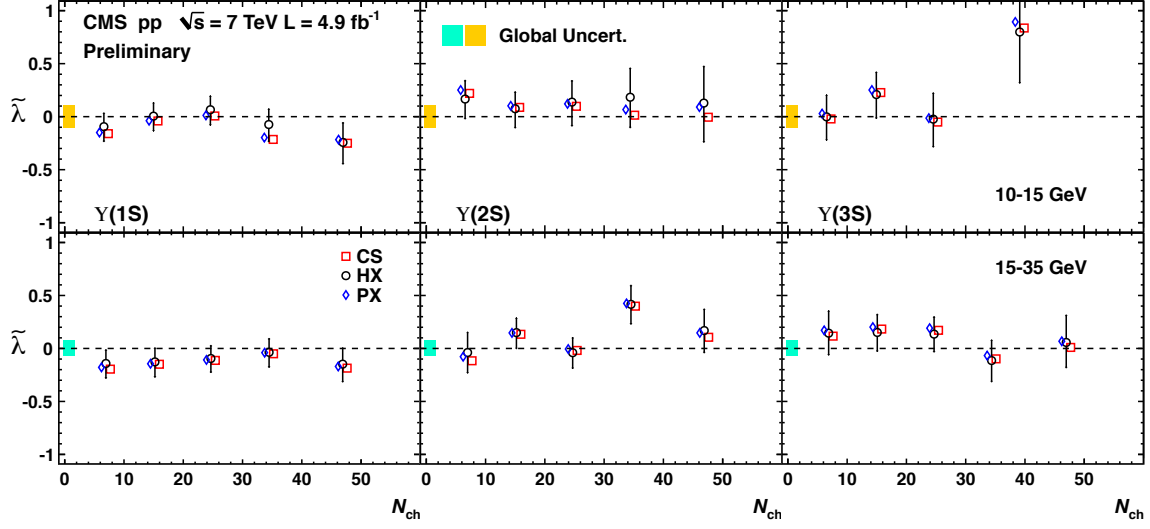
Figure 2: Frame-invariant $\tilde{\lambda}$ parameter for the $\Upsilon(1S)$ (left), $\Upsilon(2S)$ (middle) and $\Upsilon(3S)$ (right) as a function of charge particle multiplicity, N_{ch}, for $10 < p_T < 15$ GeV and $15 < p_T < 35$ GeV. The error bars represent total uncertainties at the 68.3% confidence level (CL) in the HX frame [4].

Figure 2 shows a good agreement of $\tilde{\lambda}$ values in the different reference frames, indicating that the analysis is internally consistent.

The measurement of the Υ(nS) polarizations as function of N_{ch} is performed as a first step in a broader study of polarization effects in nuclear media with the goal to extend the polarization measurements to CMS heavy ion collisions data.

2. Heavy flavour production in Run I

The $B_c^{\pm}$ meson is the lightest particle consisting of two differently-flavoured heavy quarks. CMS observed B_c^+ (charge conjugation is implied) in the kinematic region $p_T > 15$ GeV and $|y| < 1.6$ decaying to $J/\psi\pi^+$ and $J/\psi\pi^+\pi^+\pi^-$. The ratio of the production cross sections times branching fractions of $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ has been determined to be $[0.48 \pm 0.05$ (stat.) ± 0.03 (syst.) ± 0.05 (B_c lifetime, τ_{B_c})]%, using B^+ candidates in the same kinematic region as the B_c^+. Moreover, the ratio $(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)/(B_c^+ \to J/\psi\pi^+)$ is measured to be 2.55 ± 0.80 (stat.) ± 0.33 (syst.)$^{+0.04}_{-0.01}$ (τ_{B_c}), which is consistent with the previous LHCb result [15].

3. First look at Run II data

Dimuon invariant mass distributions collected with dedicated dimuon triggers at $\sqrt{s} = 13$ TeV are shown in Fig. 3. About one third of the integrated luminosity already collected by the CMS experiment up to the EPS conference are used. In total, the LHC is expected to deliver about 2 to 3 fb^{-1} of data until the end of 2015.
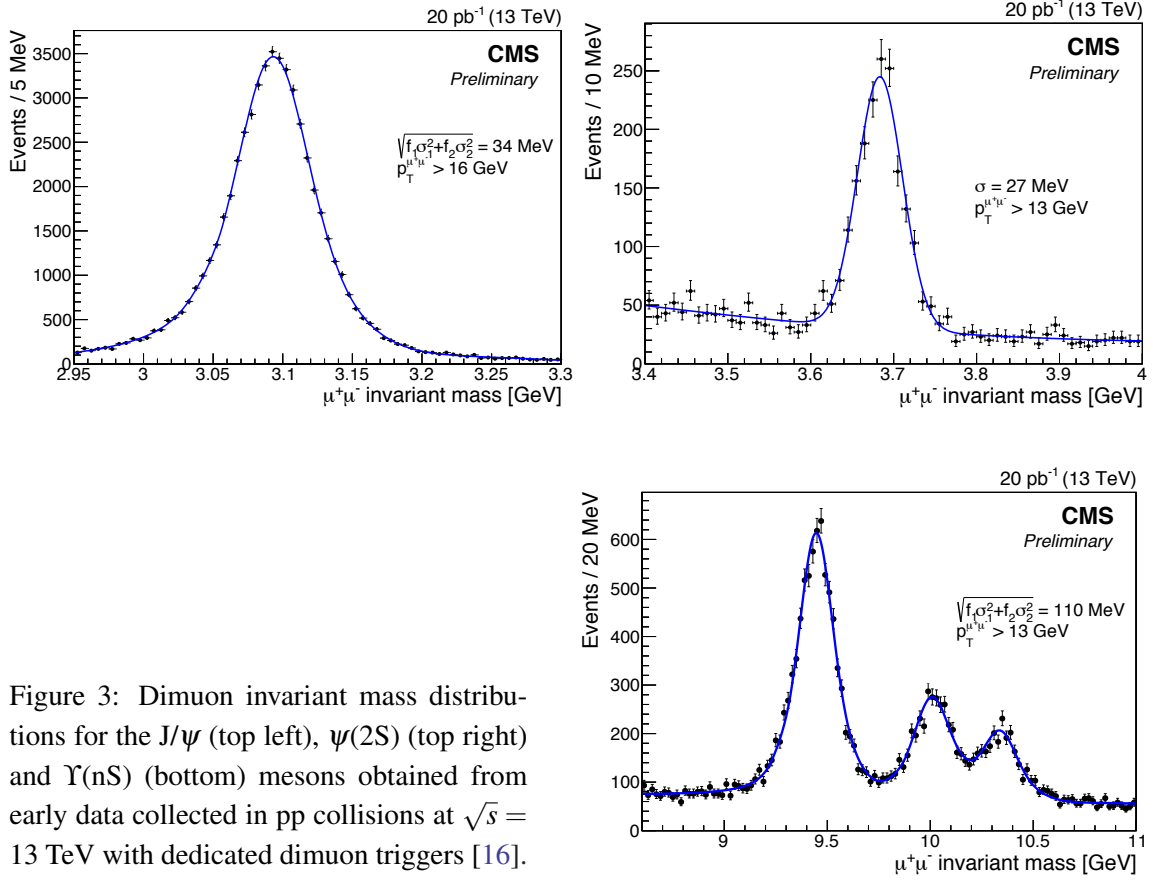
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Figure 3: Dimuon invariant mass distributions for the J/ψ (top left), ψ(2S) (top right) and Υ(nS) (bottom) mesons obtained from early data collected in pp collisions at $\sqrt{s} =$ 13 TeV with dedicated dimuon triggers [16].

4. Summary and conclusions

The CMS experiment already published numerous results on quarkonium and heavy flavour production using Run I data. Only a few selected results on S-wave cross sections, the Υ(nS) polarizations as function of N_{ch} and B_c^+ mesons decaying to J/$\psi\pi^+$ and J/$\psi\pi^+\pi^+\pi^-$ have been discussed here. Moreover, first distributions obtained with $\sqrt{s} =$ 13 TeV have been presented.

The data collected during the LHC Run I have not been fully exploited yet: many more interesting measurements are possible like the polarizations of P-wave states. Additionally, new data collected at a never before achieved energy offers new opportunities and challenges and promise exciting times ahead.

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