PROCEEDINGS OF SCIENCE

Heavy flavour production at CMS

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Three recent results in heavy flavour production at the CMS experiment are addressed in this report. Measurements of the differential production cross sections of B hadron and quarkonium states in pp collisions at $\sqrt{s} = 13$ TeV are presented. These are important tools to investigate heavy-quark production mechanisms in QCD. The dependences on transverse momentum and rapidity are investigated and comparisons with theory expectations and among different collision energies are provided. Also the new observation of $\Upsilon(1S)\Upsilon(1S)$ production is reported.

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1. Introduction

In heavy flavour physics there are still some aspects that remain to be understood, like the apparent contradictions in NRQCD between the shapes of differential cross sections and polarizations for the quarkonia states (non-observation of transverse polarization predicted at LO, non-identification of the expected correction at large p_T). A good apparatus to study the production mechanism of the b-hadrons and the quarkonium states can help in clarifying the situation. The CMS experiment is a multi-purpose detector and provides good results in the field of B physics thanks to its excellent dimuon mass resolution ($\sim 0.6-1.5\%$ depending on |y|), good muon identification performance and triggers able to cope with the large LHC rates, together with a large tracking coverage up to $|\eta| < 2.4$. The Run 1 of LHC has already provided several experimental information and now, with the 13 TeV pp collisions, the Run 2 can improve the precision of the production measurements in the high-p_T region, where the theoretical predictions are most reliable. This report presents the B^+ and quarkonium production cross section analyses in Sections 2 and 3 respectively and the double $\Upsilon(1S)$ production analysis is presented in Section 4.

1.1 The CMS trigger system

The CMS detector collects data with a 2-level trigger: an hardware-based trigger called *L1*, with a rate of $\sim$ 100 kHz, and a software trigger called *HLT*, with full information from tracking and vertex reconstruction, which decreases the event rate to less than 1 kHz. The different CMS analyses use specific triggers developed for them: the quarkonia, B_S and non resonant dimuon triggers are employed in the flavour physics analyses. In particular the B^+ analysis relies on a displaced J/ψ vertex trigger and on a combination with a charged track, the quarkonium analysis on a barrel-only trigger, defined by $|y| < 1.2$, and the double Υ analysis on a 3 muons trigger. Further selections on the p_T and on the pseudorapidity of the single muons and of the dimuons are required by both L1 and HLT triggers.

2. B^+ production cross section analysis

The B^+ production cross section measurement is important because at the higher energies of the Run 2 of LHC it can provide a new important test of theoretical calculations.
This measurement has been performed in the exclusive channel of B^+ decaying into $J/\psi K^+$, where the J/ψ decays into a pair of muons, and it is based on 13 TeV data with a luminosity of $\sim$ 50.8 pb^{-1} [1]. The differential cross section has been measured as a function of the transverse momentum and of the rapidity of the B hadron and is given by:

$$\frac{d\sigma(pp \to B^+X)}{d\omega} = \frac{n_{sig}(\omega)}{2\mathscr{A} \cdot \varepsilon(\omega)\mathscr{B}\mathscr{L}\Delta\omega}$$

where $\omega = p_T^B, |y^B|$ and $\mathscr{B}$ is the total BR, given by the individual BR of B^+ decaying into $J/\psi K^+$ multiplied by the BR of J/ψ decaying into a pair of muons. The factor 2 in the denominator reflects the choice to quote the cross section for a single charge, while the yields include both charge states. In this analysis the detection efficiencies and the geometrical acceptance are evaluated through simulation studies using large sample of B^+ signal, while the trigger and muon reconstruction

efficiencies are measured from a data sample of inclusive $J/\psi \to \mu^+\mu^-$ decays.
The yield extraction is performed with an extended unbinned maximum likelihood fit. In Figure 1 the fit to the invariant mass distribution of the B^+ candidates in the full p_T region is reported.

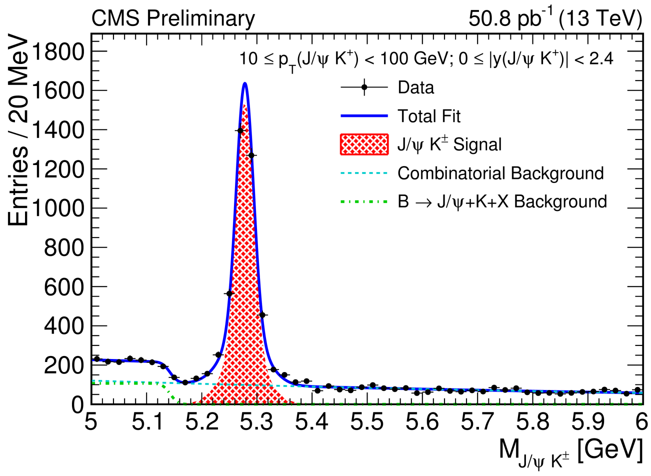

Figure 1: *B^+ invariant mass distribution: signal component in red, combinatorial background (coming from inclusive J/ψ production) in light blue and mis-reconstructed background (arising from b-hadrons decays such as $B \to J/\psi + K + X$ and producing a broad structure in the mass region below 5.15 GeV) in green.*

2.1 Results and comparisons

The B^+ differential production cross section results at 13 TeV are reported in Figure 2. The 13

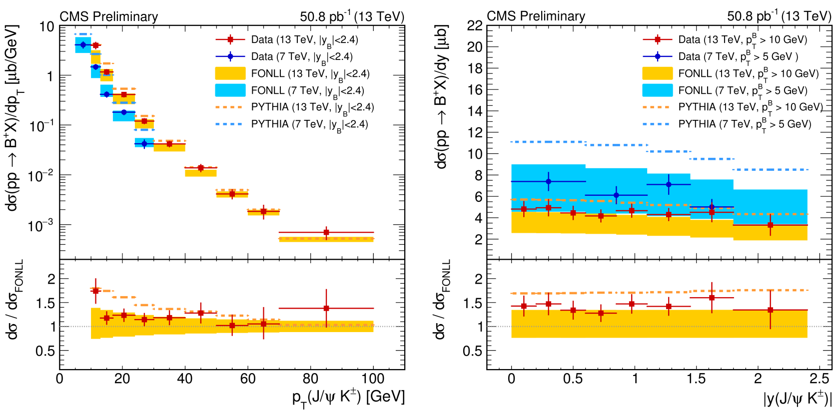

Figure 2: *B^+ cross section results as a function of p_T for $|y^B| < 2.4$ on the left and as a function of rapidity for $10 < p_T < 100$ GeV on the right: 13 TeV data (red markers), 7 TeV data (blue markers), PYTHIA (dashed lines) and FONLL calculations (boxes) are shown. The bottom panels show the cross section ratios between data and FONLL calculations.*

TeV and 7 TeV data are compared with PYTHIA and FONLL calculations, showing a reasonable

agreement both in terms of shape and of normalization.
The systematics uncertainties are dominated by the muon efficiencies and by the modeling of the signal and the background.

3. Quarkonium production cross sections analysis

The study of quarkonium production in hadronic collisions has been subject of interest in a large number of experiments since the discovery of heavy-quark bound states and now, with the comparison between the 13 TeV and 7 TeV results, it can provide a good opportunity to test the factorization hypotheses of NRQCD.
The measurement of five S-wave quarkonium states (J/ψ, $\psi(2S)$, $\Upsilon(12)$, $\Upsilon(2S)$, $\Upsilon(3S)$) has been performed on 13 TeV data with a luminosity of 2.4 (2.7) fb^{-1} for J/ψ (other states) [2]. The double differential production cross section, multiplied by the BR of the meson decaying into a pair of muons, is calculated in several dimuon p_T and rapidity bins and is given by:

$$BR(q\bar{q} \to \mu\mu) \times \frac{d^2\sigma^{q\bar{q}}}{dp_T dy} = \frac{N^{q\bar{q}}(p_T, y)}{\mathscr{L}\Delta y \Delta p_T} \cdot < \frac{1}{\varepsilon(p_T, y)\mathscr{A}(p_T, y)} >$$

where the acceptance times efficiency term is averaged over all the events in the bin.
For this analysis an unpolarized production is assumed and a kinematical range with $p_T(\mu\mu) > 20$ GeV and $|y(\mu\mu)| < 1.2$ is used. Further requirements on p_T are applied on single muons, in order to perform the measurement in a kinematical region where the muon acceptance is high.
The yields are determined with an extended unbinned maximum likelihood fit to the mass distribution for the $\Upsilon(nS)$ states. For the charmonium states an additional non-prompt component, originating from the decays of b-hadrons, must be taken into account. The yields and non-prompt fractions are then measured with a 2D fit to the invariant mass and decay length distributions.
Both acceptance and efficiencies corrections are based on per-event calculations. The acceptance is calculated using simulated events, while the efficiency is derived using a data-driven Tag&Probe procedure. The dimuon efficiency is obtained as the product of the two single muons efficiencies, multiplied by a correction factor that takes into account the correlation between the two muons and becomes increasingly important when the two muons are close to each other in the phase space and the L1 trigger fails to distinguish them.

3.1 Results and comparisons

The double differential cross sections at 13 TeV have been measured for the five S-wave quarkonium states and are reported in Figure 3 as a function of p_T. The cross sections are calculated in 2 rapidity bins for the Υ mesons and in 4 rapidity bins for J/ψ and $\psi(2S)$.
The 13 TeV results are compared with the 7 TeV ones and are presented in Figure 4. For all the five quarkonium states the 13 TeV cross sections tend to follow the trend observed in the 7 TeV data, changing slowly as a function of p_T of dimuon, but they scale up by a factor of 2-3. An increase of this order is expected from the evolution of parton distribution functions, even if a detailed comparison with the theory awaits an updated calculation of NRQCD at 13 TeV.
Also the production cross sections of the radial excitation states relative to the ground states have been performed and these ratios are reported in Figure 5.

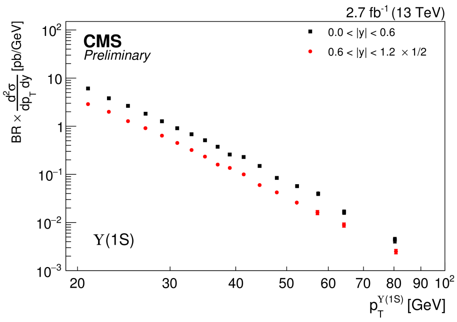

Figure 3: *Differential cross section results as a function of p_T for $\Upsilon(1S)$ on the left and for J/ψ on the right. The errors bars represent the statistical uncertainty and the sum in quadrature of statistical and systematic uncertainties, which are dominated by muon efficiencies.*

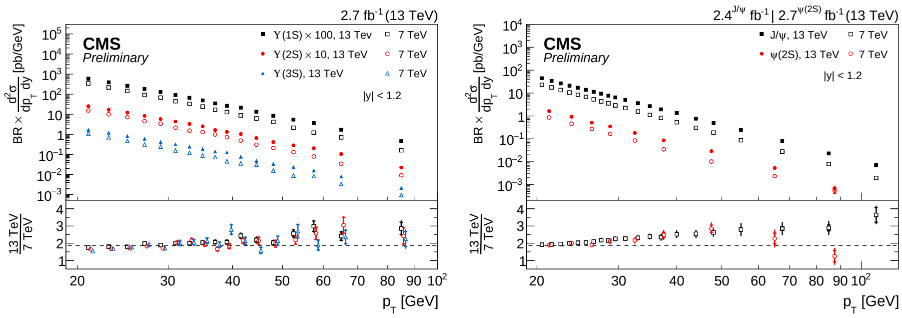

Figure 4: *Comparison between 13 TeV and 7 TeV cross sections for $\Upsilon(12)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ on the left and for J/ψ and $\psi(2S)$ on the right. The bottom panels show the cross section ratios of the 13 TeV over the 7 TeV results as a function of p_T.*

Finally the charmonium non-prompt fractions have been measured as a function of p_T and are illustrated in Figure 6, where the good agreement between 13 TeV and 7 TeV data is visible.

4. Double $\Upsilon(1S)$ production analysis

Even if the production of double quarkonium has been a source of interest since the observation of the first J/ψ pair production at NA3 experiment in 1982, the Υ-pair production has never been observed in any experiment so far. New findings in this frontier will then potentially benefit other measurements like rare Higgs decay to pair of quarkonium and resonance searches for b bound states, enhance the sensitivity of matrix element calculation for SPS production and allow to test factorization hypotheses for DPS production.
This measurement is based on 8 TeV data acquired in 2012 with a luminosity of $\sim 20.7\ fb^{-1}$ and is performed considering both the $\Upsilon(1S)$ mesons decaying isotropically into two muons [3]. The production cross section is given by:

$$\sigma(pp \to \Upsilon\Upsilon) = \frac{N^{\Upsilon\Upsilon}}{BR(\Upsilon \to \mu\mu)^2 \cdot \mathscr{L}} \cdot < \frac{1}{\varepsilon \cdot \mathscr{A}} >$$

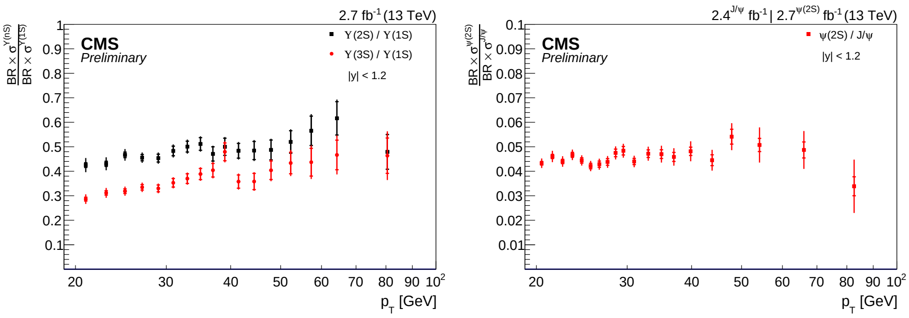

Figure 5: *Differential cross section ratios as a function of p_T for $\Upsilon(2S)$ and $\Upsilon(3S)$ over $\Upsilon(1S)$ on the left and for $\psi(2S)$ over J/ψ on the right.*

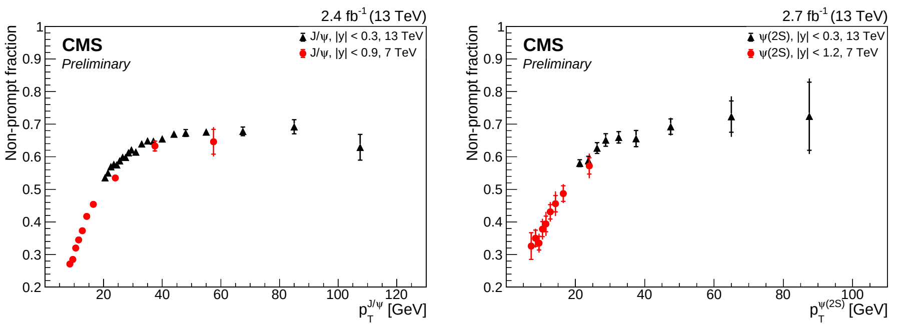

Figure 6: *Comparison between 13 TeV and 7 TeV non-prompt fractions as a function of p_T for J/ψ on the left and for $\psi(2S)$ on the right.*

where the inverse product of per-event efficiencies and acceptance is averaged for all the events with efficiencies $> 1\%$. The acceptance and efficiencies corrections are calculated event per event using the measured momenta of Υ meson and muons.
The invariant mass of the Υ meson with higher mass and the invariant mass of the Υ meson with lower mass are used to discriminate the signal from the background. From the 2D plot of invariant mass in Figure 7 a clear excess of $\Upsilon(1S)\Upsilon(1S)$ events is visible.
The signal extraction is performed with a 2D unbinned maximum likelihood fit over the entire rapidity range of the Υ meson and the simultaneous Υ events are the product of the signal PDF from each dimuon. The fit results projected on the invariant mass distribution are reported in Figure 8.

4.1 Results

The simultaneous $\Upsilon\Upsilon$ events are observed for the first time with a signal yield of 38 ± 7 events and with a statistical significance of 9.6 standard devations. The preliminary cross section of simultaneous production of two $\Upsilon(1S)$ mesons within the Υ acceptance region is:

$$\sigma_T = 68.8 \pm 12.7(stat) \pm 7.4(syst) \pm 2.8(BR) pb$$

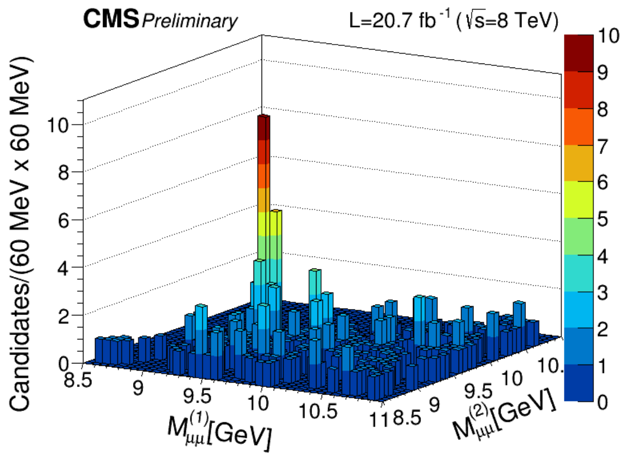

Figure 7: *2D invariant mass plot for $\Upsilon\Upsilon$ events.*

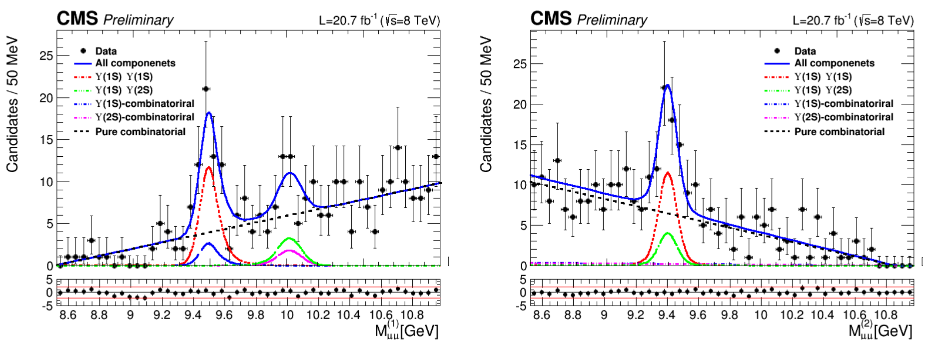

Figure 8: *Invariant mass distributions for the muon pairs with higher mass on the left and for the muon pairs with lower mass on the right.*

where the systematic uncertainties are dominated by the modeling of the PDF, but the cross section uncertainty is dominated by statistics ($\sim 20\%$).
An unpolarized production of Υ mesons was assumed in the default measurement, then also studies for different polarization scenarios were carried out. The cross section is expected to change between $(+36\%, -38\%)$, assuming the extreme polarization scenarios: the longitudinal ($\lambda = +1$) and transverse ($\lambda = -1$) polarizations.

References

[1] *Measurement of the B^+ hadron production cross section in pp collisions at 13 TeV*. Technical Report CMS-PAS-BPH-15-004, CMS Collaboration, CERN, Geneva, 2015.

[2] *Quarkonium production cross sections in pp collisions at* $\sqrt{s} = 13$ TeV. Technical Report CMS-PAS-BPH-15-005, CMS Collaboration, CERN, Geneva, 2016.

[3] *Observation of $\Upsilon(1S)$ pair production at CMS*. Technical Report CMS-PAS-BPH-14-008, CMS Collaboration, CERN, Geneva, 2016.