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PROSPECTS FOR HADRON SPECTROSCOPY AT THE CMS EXPERIMENT

Roberto Covarelli
Universitá degli Studi-INFN di Perugia

Abstract

The CMS detector at the LHC will be able to detect hadron production at an unprecedented center-of-mass energy of 14 TeV. We present dedicated simulation studies for the measurement of the B_c^+-meson mass and lifetime using the exclusive decay channel $B_c^+ \to J/\psi\pi^+$. Moreover, quarkonium reconstruction capabilities in CMS are presented in terms of efficiency and expected resolution both in proton-proton collisions (J/ψ reconstructed from the $B_s^0 \to J/\psi\phi$ decay channel) and in heavy ion collisions.

1 The CMS detector

CMS [1] is a multi-purpose solenoidal detector designed for 7 TeV-7 TeV proton beam collisions at the Large Hadron Collider (LHC).

Its innermost detector is a large silicon tracking device: the inner part consists of 3 (2) layers of silicon pixels in the barrel (endcap) region, while the outer part is equipped with 10 (12) layers of micro-strip silicon detectors, providing a very good tracking efficiency and transverse momentum resolution up to high values of the pseudo-rapidity.

For a precise determination of electron and photon energies, an electromagnetic calorimeter, consisting of over 80,000 lead-tungstate ($PbWO_4$) crystals, equipped with avalanche photodiodes or vacuum phototriodes, covers both barrel and endcap regions. Energy and direction of jets and of missing transverse energy flow in events are measured by means of hadronic sampling calorimeters with 50-mm-thick copper absorber plates interleaved with 4-mm-thick scintillator sheets.

The calorimeters are surrounded by a superconducting coil that provides a solenoidal magnetic field of 4 T.

The return yoke of the magnet is made of iron and equipped with chambers used to detect muons. Drift Tubes and Resistive Plate Chambers are used in the barrel region, while Cathode Strip Chambers and Resistive Plate Chambers cover the two endcap regions, giving a very good efficiency for muon detection and a solid-angle acceptance close to 4π.

The trigger of the experiment [2)] is divided in two levels: the Level 1 (L1) is a hardware-based trigger, using only information from muon chambers and calorimeters. Transverse momentum thresholds are expected to be as low as 6 GeV/c for single muons, while they can reach 3 GeV/c for dimuons in a low-luminosity scenario. The other trigger level, the High Level Trigger (HLT) uses information from the whole event: at this stage partial track reconstruction and vertexing from the tracking systems, as well as invariant mass of simple composite candidates, can be exploited to define a number of highly efficient trigger streams. Most analyses discussed in this paper are based on the opposite-sign dimuon HLT stream.

2 The LHC Data-Taking Plans

The LHC will start delivering beams in 2008 and will be operated in different conditions:

- for most of the data-taking time, proton-proton beams will be circulated and collided at a center-of-mass energy of 14 TeV. After the start-up, two luminosity scenarios can be foreseen according to the machine design:

the low-luminosity scenario, as assumed in CMS analyses, is based on a luminosity value of $\mathcal{L}_{\rm low} = 2 \times 10^{33}$ cm^{-2}s^{-1}, while, after some years of operation, this value is expected to reach $\mathcal{L}_{\rm high} = 10^{34}$ cm^{-2}s^{-1} (high-luminosity scenario).

- for about one twelfth of the running time, heavy ion beams will replace the proton beams. Most of these will be ^{208}Pb-^{208}Pb collisions at a center-of-mass energy of 5.5 TeV. The expected luminosity is $\mathcal{L}_{\rm ions} = 4 \times 10^{26}$ cm^{-2}s^{-1}, posing a significant challenge to CMS, due to the extreme occupancy of the inner detectors in these conditions.

3 Heavy Flavor Physics at CMS

The CMS physics program is mostly devoted to searches related to Higgs and new physics particles [3]. Heavy flavor physics is also a field where many interesting measurements can be carried out, both in terms of hadron production and decays, especially in the low-luminosity scenario. Heavy flavor processes are also interesting because they can constrain indirectly transitions that involve scales much higher than m_b, through loop propagation of new particles.

Dedicated experiments for heavy flavor and heavy ion physics are being designed for LHC. These experiments will take some advantage over CMS, having large acceptance, excellent hadron identification possibilities and lower $p_\perp$ muon triggers. On the other hand, CMS will have a very good muon resolution and acceptance, due to the muon chamber coverage, the high magnetic field and the full-silicon tracker. These characteristics can allow CMS to perform heavy flavor analyses also in a high-luminosity scenario.

4 J/ψ Reconstruction Studies

Charmonium is mainly detected in the $J/\psi \to \mu^+\mu^-$ decay channel [4]. The large production cross section predicted at LHC for both prompt J/ψ and J/ψ from b-hadron decays will allow for an accurate understanding of muon reconstruction performances.

The study of this decay channel has been performed using a large sample of J/ψ ($\sim$200 000) from Monte Carlo simulation of events where the $B_s^0 \to J/\psi\phi$ decay is forced, with the J/ψ decaying into muons. The reconstruction efficiency has been determined both for single muons and for J/ψ candidates and has been studied as a function of $p_\perp$, $|\eta|$ and $\Delta\Omega_{\mu\mu}$, i.e. the 3-dimensional angular separation of the muon pair. The efficiency has been calculated at different analysis levels: applying geometric acceptance cuts only, after J/ψ candidate reconstruction, after L1 decisions and HLT decisions, as defined in Sec. 1.

From this study we conclude that:

- The offline reconstruction efficiency for $J/\psi \to \mu^+\mu^-$ is about 10.1% averaging on all values of $p_\perp(J/\psi)$, while is in the range 50-70% for $p_\perp(J/\psi) > 20$ GeV/c. The mass resolution is 34 MeV/c^2.
- The efficiency is slightly reduced for small and large angles of $\Delta\Omega_{\mu\mu}$. Small values of $\Delta\Omega_{\mu\mu}$ happen mainly in the endcap region, close to the acceptance cut, and the efficiency loss is mainly caused by track overlap, while large values of $\Delta\Omega_{\mu\mu}$ are correlated with low-$p_\perp$ muons.
- The L1 trigger retains almost all events with large $p_\perp(J/\psi)$. A specific HLT trigger path for the J/ψ decay has been defined, removing the tracker isolation requirement on the muon tracks. Figure 1 shows the L1 and HLT efficiencies vs. $p_\perp(J/\psi)$ with different possible choices for the $p_\perp(\mu)$ threshold in the last trigger stage.

5 Study Of The Decay $B_c^+ \to J/\psi\pi^+$

The study of the $B_c^+ \equiv \bar{b}c$ meson[1] is important to test theoretical predictions of potential models, because this is the only known meson composed of two distinct heavy quarks [5]. As such, it decays only weakly, having thus a long lifetime. The theoretical expectations for the B_c^+ mass and lifetime are $m(B_c^+) = (6.24 \pm 0.05)$ GeV/c^2 and $\tau(B_c^+) = (0.54 \pm 0.15)$ ps [6].

These quantities have been measured by the CDF collaboration [7] to be:

$$m(B_c^+) = [6.2741 \pm 0.0032(\text{stat.}) \pm 0.0026(\text{syst.})]\ \text{GeV}/c^2 \qquad (1)$$

using the $B_c^+ \to J/\psi\pi^+$ channel, and:

$$\tau(B_c^+) = [0.462^{+0.073}_{-0.065}(\text{stat.}) \pm 0.036(\text{syst.})]\ \text{ps} \qquad (2)$$

[1]Charge conjugation is always implied.

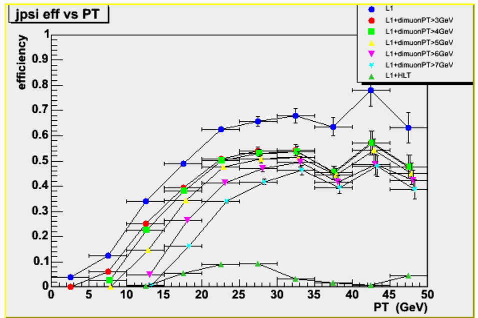

Figure 1: *Total HLT efficiency for J/ψ reconstruction as a function of the J/ψ reconstructed transverse momentum in the lab frame. The blue circles represent the efficiency after L1, the green triangles is after the default HLT requirements (isolation included). Other markers stand for the corrected HLT requirements at different values of the $p_\perp$ threshold.*

using the $B_c^+ \to J/\psi \mu^+ \nu_\mu$ channel.

The B_c^+ production rate at LHC is 16 times larger than at the Tevatron, so experiments at LHC could potentially collect many more B_c^+ mesons. In CMS the only decay mode studied so far is $B_c^+ \to J/\psi \pi^+$.

The signal event generation is performed using a dedicated generator for B_c^+ physics (BCVEGPY), while comparison with PYTHIA is used to estimate systematics from the theoretical B_c^+ production model. The backgrounds considered are: J/ψ production from other b-hadron decays (B^0, B^+, B_s^0 and Λ_b), prompt J/ψ production, both in color singlet and octet states, semileptonic decays $b\bar{b}$, $c\bar{c} \to \mu^+\mu^- X$, as well as W, Z plus jets and generic QCD events. Trigger requirements are applied at generator level to achieve an affordable event generation time.

A cut-based selection is then applied:

- A kinematically-constrained vertex fit to the muon pair is required to converge.
- The muon pair invariant mass must lie between 3.0 and 3.2 GeV/c^2.
- The dimuon mass is then constrained to the nominal J/ψ mass and a charged track (π) is added to make the B_c^+ candidate. We require

$p_{\perp}(\pi) > 2.4$ GeV/c, $|\eta(\pi)| < 2.2$ and that it must pass a muon-ID veto.

- The proper decay length in the transverse plane must be greater than 60 μm, while the corresponding decay length in the CMS frame must have a significance of 2.5 at least.

- Finally, the cosine of the pointing angle, i.e. the angle between the B_c^+ momentum direction and the line connecting the primary and secondary vertices, must be greater than 0.8.

With this selection, we obtain a very good signal-to-background ratio in a mass window of 200 MeV/c^2 around the generated B_c^+ mass (6.4 GeV/c^2). The number of selected signal and background events is respectively 120 ± 11 and 2.6 ± 0.4 in a Monte Carlo equivalent integrated luminosity of 1 fb^{-1}.

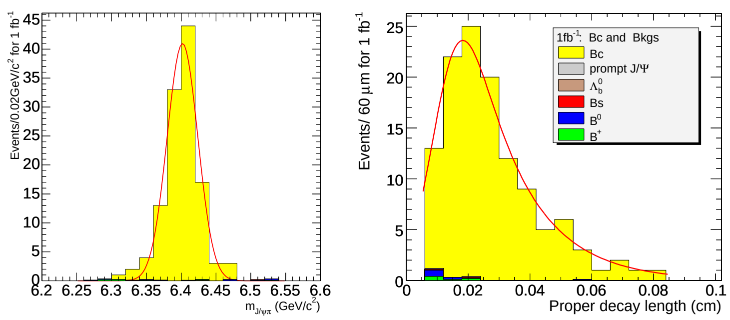

Figure 2: *Left: Gaussian fit to the $J/\psi\pi^+$ invariant mass distributions. Right: Fit to the B_c^+ proper decay time distribution with an exponential convolved to a resolution function. Various background components are superimposed to the total distributions.*

Fits to the mass and lifetime distributions are shown in Figure 2. The results of the fits are:

$$m(B_c^+) = [6.402 \pm 0.002(\text{stat.})]\ \text{GeV}/c^2 \quad \text{generated} = 6.400\ \text{GeV}/c^2 \quad (3)$$

$$c\tau(B_c^+) = [149 \pm 13(\text{stat.})]\ \mu\text{m} \quad \text{generated} = 150\ \mu\text{m}, \quad (4)$$

showing that no biases are induced by the selection procedure.

Preliminary systematic studies have been performed, considering as possible sources of uncertainty: the tracker and muon chamber misalignment, the limited background Monte Carlo statistics, possible cut variations and the theoretical model assumed in B_c^+ production processes. The final expected uncertainties are:

$$[\pm 0.002(\text{stat.}) \pm 0.015(\text{syst.})]\ \text{GeV}/c^2$$

on $m(B_c^+)$, and

$$[\pm 0.044(\text{stat.}) \pm 0.010(\text{syst.})]\ \text{ps}$$

on $\tau(B_c^+)$.

The main systematic uncertainty on the mass is coming from a worst-case misalignment scenario. With real data, a a more realistic study of the systematic errors can be obtained. Also, control samples like $B^+ \to J/\psi K^+$ can be used to understand and keep under control misalignment effects.

6 Quarkonium Production In Heavy Ion Collisions

Heavy ion collisions are important because they allow matter to reach temperatures of the order of the critical temperature $T_c \sim 180$ MeV, where QCD predicts quark deconfinement and therefore the possible formation of quark-gluon plasma (QGP). Matsui and Satz [8] have shown that one of the experimental signatures of QGP formation is a suppression of quarkonia yields: QGP can, in fact, screen the color-binding potential, preventing heavy quarks from forming bound states.

Many experiments have been devoted to measuring this effect. NA38 first reported a smooth J/ψ suppression with respect to the Drell-Yan dimuon production, that could also be explained by nuclear absorption of charm quarks. The first evidence of departure from the nuclear absorption scheme was found by NA50 [9] and the measured suppression factor was 0.77 ± 0.04. RHIC experiments are now taking data with Pb-Pb collisions at a canter-of-mass energy of 200 GeV. Recent studies [10] have shown that J/ψ could survive at a temperature as high as $1.5T_c$, that could be out of range for RHIC: in this case, Υ production measurements also become interesting.

In CMS we determine ψ and Υ quarkonia yields in the dimuon decay channel, within the nominal Pb-Pb collision luminosity scenario [11]. Since quarkonia cross-sections are many orders of magnitudes smaller than the total inelastic Pb-Pb cross-section, full simulation of events would require a too large amount of time and data to be performed. Events are therefore generated using a fast simulation technique, that includes theoretical production models and detector effects.

Signal consists of events containing J/ψ, ψ', Υ, Υ' or Υ'' states decaying to $\mu^+\mu^-$, where $\sigma_{prod} \cdot BR_{\mu^+\mu^-}$ is about 50 mb for the sum of the ψ states and 400 μb for the sum of the Υ states.

The backgrounds considered are:

- muons from decays in flight of soft hadrons (π/K) coming from the nucleus-nucleus collision. Two cases are considered, the first with a high charged particle multiplicity for central collisions ($dN^{\pm}/d\eta|_{\eta=0} = 5000$) and the second with a lower multiplicity ($dN^{\pm}/d\eta|_{\eta=0} = 2500$), based on the extrapolation of RHIC measurements to the LHC energies.
- muons from open c- and b-hadron pair production (estimated with the PYTHIA generator).

The detector effect simulation is done in steps. Trigger efficiencies are considered using muon trigger tables in $p_\perp$ and η bins. Muon and di-muon reconstruction efficiencies are also estimated vs. $p_\perp$ and η for the different background types. Resolutions found in invariant mass distributions (34 MeV/c^2 for J/ψ, 85 MeV/c^2 for Υ) are used as smearing factors in the fast simulation. The resulting quarkonia acceptance (1.3% for J/ψ, 23% for Υ) is taken into account.

The invariant mass distributions from fast simulation samples are shown in Figure 3 top, where the Monte Carlo has been rescaled to an equivalent luminosity of 0.5 nb^{-1} (one month data-taking). Figure 3 bottom shows how a better signal-to-background ratio can be attained by requiring both muons to be in the barrel detectors, but the significance is actually lower, so this cut is not applied. Background subtraction is done using bin-by-bin distributions of same sign dimuon combinations and using the estimate:

$$N_{signal} = N^{+-} - 2\sqrt{N^{++}N^{--}} \tag{5}$$

No evidence is found of a ψ' measurable yield. All other yields are summarized in Tables 1 and 2.

Table 1: *$c\bar{c}$ quarkonia yields in the two multiplicity scenarios considered.*

	$N(J/\psi)$	S/B
$dN^{\pm}/d\eta\|_{\eta=0} = 2500$	180 000	1.2
$dN^{\pm}/d\eta\|_{\eta=0} = 5000$	150 000	0.6

Table 2: *$b\bar{b}$ quarkonia yields in the two multiplicity scenarios considered.*

	$N(\Upsilon)$	$N(\Upsilon')$	$N(\Upsilon'')$	S/B
$dN^{\pm}/d\eta\|_{\eta=0} = 2500$	25 000	7 300	4 400	0.12
$dN^{\pm}/d\eta\|_{\eta=0} = 5000$	20 000	5 900	3 500	0.07

The main systematic uncertainty associated to the Monte Carlo result comes from the limited background statistics of the fast-simulated sample that enters the reweighting technique: this has currently a relative impact on the yield of $\sim 20\%$ for J/ψ and $\sim 25\%$ for Υ. Comparison between fast and full simulation gives results well within these uncertainties, so it does not contribute significantly.

Other systematic uncertainties are related to limitations in detector description, the results being extremely sensitive to the dependence of the tracker efficiency on the multiplicity of the event. The amount of these effects can be determined by comparing reconstructed states using muon chambers only and tracker plus muon chambers, at each tracker occupancy level.

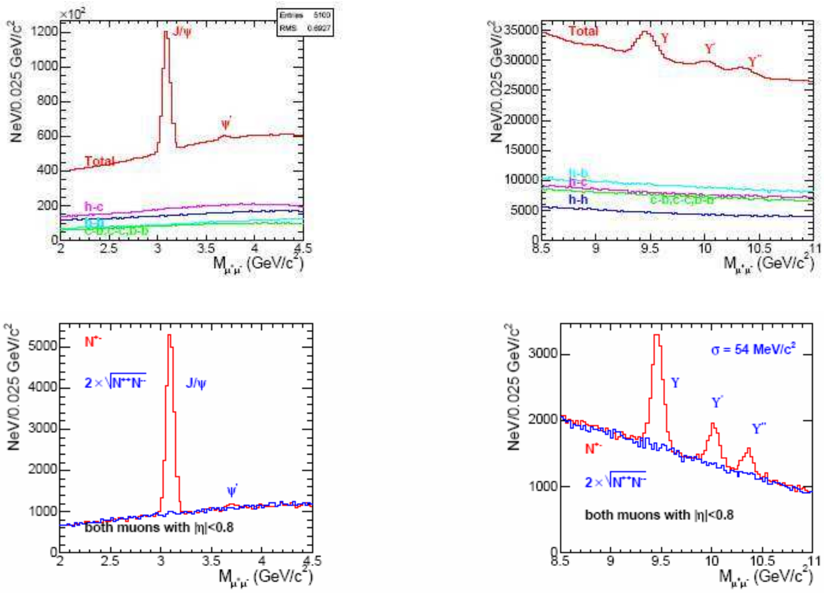

Figure 3: *Top: The invariant mass distributions from quarkonia simulated samples in the* ψ *(left) and* Υ *(right) mass regions for the low-multiplicity scenario (*$dN^{\pm}/d\eta|_{\eta=0} = 2500$*). All considered backgrounds are added and detailed in the figures (c or b stand for c- or b-hadron decays, h is either a K or a* π *produced in the collision). Bottom: The same distributions with both muons in the CMS barrel region (*$|\eta| < 0.8$*, in red). Same-sign dimuon distributions are also superimposed (in blue) to show effectiveness of the background subtraction technique.*

7 Summary

We have shown the potentials of the CMS detector in hadron spectroscopy by focusing on three physics topics.

We first presented the measurement of reconstruction performances of the J/ψ resonance, which is the most abundant state associated to the dimuon channel triggers. The efficiency of the HLT selection has been found to be up to 40-50% at high transverse momentum values ($p_\perp(J/\psi) > 20$ GeV/c).

An important test of potential models in the SM is provided by the measurement of the mass and lifetime of the B_c^+ meson. In the $B_c^+ \to J/\psi\pi^+$ decay mode and with 1 fb^{-1} integrated luminosity, CMS expects to obtain uncertainties of [± 0.002(stat.) $\pm$ 0.015(syst.)] GeV/c^2 on $m(B_c^+)$ and of [± 0.044(stat.) $\pm$ 0.010(syst.)] ps on $\tau(B_c^+)$. This precision is comparable to that obtained by CDF, provided a more realistic understanding is reached of the systematics from misalignment effects. This can be achieved using control samples from data, like $B^+ \to J/\psi K^+$.

We also presented the capabilities of detecting quarkonia in heavy ion collisions. This could allow one to measure suppressions in the quarkonia production that would represent a hint of QGP formation. Up to 180 000 J/ψ and 36 000 Υ mesons can be cleanly reconstructed in the first 0.5 nb^{-1} of data, using a background subtraction technique based on same-sign dimuons.

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