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Flavor Physics Techniques and Sensitivities at ATLAS and CMS

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ATLAS and CMS have a broad heavy-flavor physics program, ranging from charmonium and bottomonium studies, to the study of the properties of the *b* hadrons, to the search for rare decays sensitive to new physics effects. We review in this paper some of the expected measurements by ATLAS and CMS with particular attention to the measurements foreseen on the data collected in the first physics run at the LHC expected toward the end of 2009.

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1. Introduction

The study of heavy-quark production will be a key early goal for ATLAS [1] and CMS [2], both in terms of physics potential and in confirming the success of the detector commissioning effort by measuring known physics processes. Even at a lower startup energy of $\sqrt{s} = 10\,\mathrm{TeV}$, the cross section for $c\bar{c}$ and $b\bar{b}$ production is large enough to provide on the order of $\mathscr{O}(10000)$ triggered and fully reconstructed $J/\psi \to \mu^+\mu^-$ and $\Upsilon(1\mathrm{S}) \to \mu^+\mu^-$ decays and $\mathscr{O}(100)$ B^+ and B^0 decays per pb^{-1}. A sample of calibrated data on the order of 10 pb^{-1} therefore provides an opportunity to use heavy-quark decays as one of several early checks on the detector tracker alignment and overall performance. With larger integrated luminosities, of the order of $\mathscr{O}(1-10$ fb$^{-1})$, the heavy-flavor physics program at ATLAS and CMS will be enriched by the study of the properties of b hadrons (meson and baryons), complementing the Tevatron program. The study of rare decays and processes sensitive to new physics effects beyond the Standard Model will be possible: the measurement of oscillations and CP violation effects in the B_s^0 system, the study of Flavor Changing Neutral Current rare B decays (e.g. $B_{u,d} \to K^{(*)}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$) or Lepton Flavor Violation processes (e.g. $\tau^+ \to \mu^+\mu^-\mu^+$).

2. Heavy Quark Production at LHC

Three processes dominate J/ψ hadro-production: prompt J/ψ's produced directly, prompt J/ψ's produced indirectly (via decay of heavier charmonium states such as χ_c), and non-prompt J/ψ's from the decay of a B hadron. It is the prompt production of quarkonia which continues to be particularly puzzling. There are a variety of production models available for prompt quarkonium production [3, 4, 5], among which are the Color Singlet Model (CSM) and the Color Octet Mechanism (COM). The latter owes its popularity to the fact that it is able to reproduce the CDF J/ψ differential-p_T cross section data [5, 6, 7]. However, the polarization predictions of the COM are in strong disagreement with measurements [8, 9]. In view of the puzzling situation, and given the large yields of quarkonia which will be produced at the LHC, the early data collected by ATLAS and CMS present an excellent opportunity to study quarkonia.

The dominant b quark production mechanism at the LHC is believed to be pair production through the strong interaction. The QCD production mechanisms are usually divided in the following categories:

- Flavor Creation (FC): it refers to the lowest order two-to-two QCD $b\bar{b}$ production diagrams. This process includes $b\bar{b}$ production through $q\bar{q}$ annihilations and gluon fusion, plus higher-order corrections to these processes. Because this production is dominated by two-body final states, it tends to yield $b\bar{b}$ pairs that are back-to-back in the azimuthal angle $\Delta\phi$ and balanced in p_T.

- Flavor Excitation (FE): it refers to diagrams in which a $b\bar{b}$ from the quark sea of the proton is excited into the final state because one of the quarks from the $b\bar{b}$ pair undergoes a hard QCD interaction with a parton from the other beam particle. Because only one of the quarks in the $b\bar{b}$ pair undergoes the hard scatter, this production mechanism tends to produce b quarks with asymmetric p_T.

- Gluon Splitting (GS): it refers to diagrams where the $b\bar{b}$ pair arises from a $g \to b\bar{b}$ splitting in the initial or final state. Neither of the quarks from the $b\bar{b}$ pair participates in the hard QCD scatter. Depending on the experimental range of b quark p_T sensitivity, gluon splitting production can yield a $b\bar{b}$ distribution with a peak at small $\Delta\phi$.

Predictions from next-to-leading-order (NLO) perturbative QCD [10] have historically underestimated both the observed inclusive b and correlated $b\bar{b}$ production cross section at the Tevatron [11]. Possible explanations for the disagreement between the measured and predicted cross-sections include b fragmentation models [12], higher-order $b\bar{b}$ production mechanisms [13], and, speculatively, supersymmetric production mechanisms [14]. In addition, a recent analysis [15] by the CDF collaboration has observed a significant previously unidentified background due to long-lived muon sources, which could account for the discrepancy between data and theory in analyses relying on muons to identify b hadrons. New data from the LHC will be a critical additional test of NLO QCD and its ability to predict accurately the expected background rates in searches for Standard Model processes (e.g., top production) and new particles (Higgs, SUSY, etc), being $pp \to b\bar{b}$ the largest physics background for many processes.

3. Trigger

All heavy-quark physics studies reported in this paper include trigger reconstruction. Both ATLAS and CMS rely primarily on single or di-muon triggers at the first level trigger (L1) , with different transverse momentum thresholds. Dedicated trigger signatures for *B*-Physics have been developed in ATLAS , based on single- and di-muon signatures with low-p$_T$ thresholds (4 GeV/c). The ATLAS trigger system is a three stage system with each stage refining decisions of previous stages with higher precision. The first level (Level 1) is implemented in hardware, whereas the decisions of the High Level Trigger (HLT), consisting of Level 2 and Event Filter (EF), are computed using a large computer farm. At Level 2, a fast muon reconstruction using precision muon chambers combined with Inner Detector measurements allow for early rejection of muons from decays in flight. In order to reduce background contributions to an acceptable level, di-muon invariant mass cuts are available as well as fast vertex fitting algorithms. At the EF level, full event data as well as alignment and calibration data are used to refine the trigger decision using offline-like algorithms.

For CMS, the single mu trigger consists of a Level 1 trigger, based on the muon chamber information, followed by a High Level Trigger (HLT) step that confirms the L1 and refines the reconstruction adding the silicon tracker information (Level 3). Many of the CMS studies presented in the following requires at least one Level 3 muon with $p_T > 3$ GeV/c (HLT_Mu3), or two Level 3 muons with $p_T > 3$ GeV/c (HLT_DoubleMu3), despite lower thresholds may be used for the first data. For both these triggers, the distance in the transverse plane between the Level 3 muon(s) and the beam spot is required to be < 2 cm.

4. Charmonium Measurements with Early Data

The measurement of the $J/\psi \to \mu^+\mu^-$ differential cross-section $d\sigma/dp_T$ will be already possible with the first $\mathscr{O}(\mathrm{pb}^{-1})$ collected by the ATLAS and CMS detectors. providing competitive

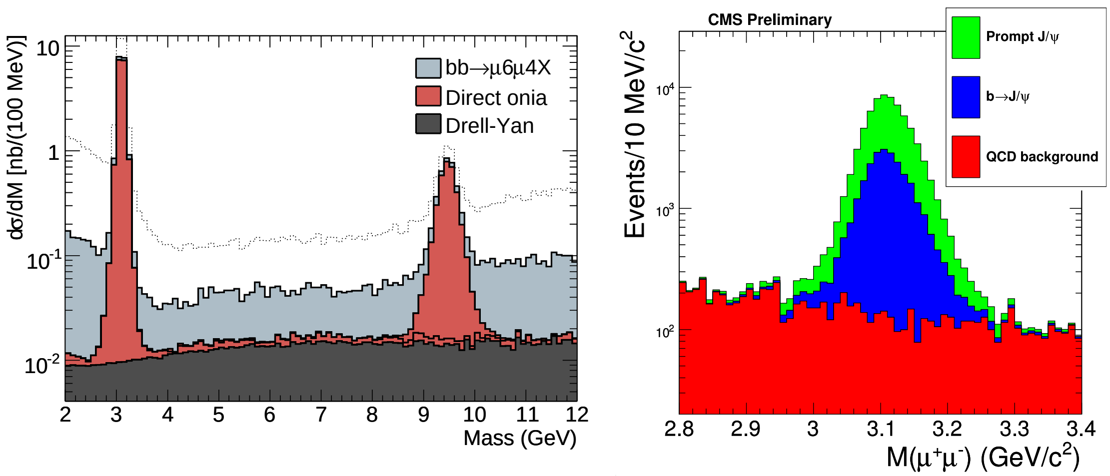

Figure 1: Left: ATLAS simulation of the invariant mass of di-muons from various sources, reconstructed with a $\mu6\mu4$ trigger, with the requirement that both muons are identified as coming from the primary vertex and with a pseudo-proper time cut of 0.2 ps. The dotted line shows the cumulative distribution without vertex and pseudo-proper time cuts. Right: CMS simulation of the dimuon invariant mass distribution normalized to 3 pb^{-1}. The green (light grey), blue (black) and red (dark grey) areas are the prompt, non-prompt and QCD background contributions, respectively.

results with respect to the Tevatron measurements over the J/ψ transverse momenta in the range from 5 GeV/c up to about 40 GeV/c.

For ATLAS [16], in each event which passes the $\mu6\mu4$ trigger (i.e. two identified muons at trigger level with p_T larger than 6 and 4 GeV/c, respectively) , all reconstructed muon candidates are combined into oppositely charged pairs, and each of these pairs is analyzed in turn. The invariant mass is calculated and, if the mass is above 1 GeV, the two tracks are refitted to a common vertex. If a good vertex fit is achieved, the pair is accepted for further analysis. If the invariant mass of the refitted tracks is within 300 MeV/c^2 of the nominal mass in the case of J/ψ, or 1 GeV/c^2 in the case of Υ, the pair is considered as a quarkonium candidate. Fig. 1 illustrates the quarkonium signal and main background invariant mass distributions in the mass range 2 - 12 GeV/c^2, with reconstruction efficiencies and background suppression cuts taken into account. Peaks from the J/ψ and Υ(1S) clearly dominate the background. No higher ψ and Υ states were simulated in this study. The dotted line indicates the level of the background continuum before the vertexing cuts.

For CMS [17], J/ψ candidates are reconstructed in events passing the HLT_DoubleMu3 trigger by pairing muons with at least 3 GeV/c transverse momentum and opposite charge. The invariant mass of the muon pair is required to be between 2.8 and 3.4 GeV/c^2. The two muons are required to come from a common vertex, which is determined by the point of their closest approach in space. The dimuon mass spectrum including background and signal is given in Fig. 1. The differential cross-section $d\sigma/dp_T$ is obtained by a 1-d fit to the J/ψ invariant mass in several different p_T intervals. The sum of two Gaussian functions is used to parameterize the J/ψ signal and a linear poynomial for the background shape. To determine the fraction f_B of J/ψ's from B-hadron decays, a 2-d unbinned Maximum Likelihood fit to the J/ψ invariant mass and the pseudo proper time ct, defined as $ct = L_{xy} \cdot m(J/\psi)/p_T(J/\psi)$ where L_{xy} is the distance in the transverse plane

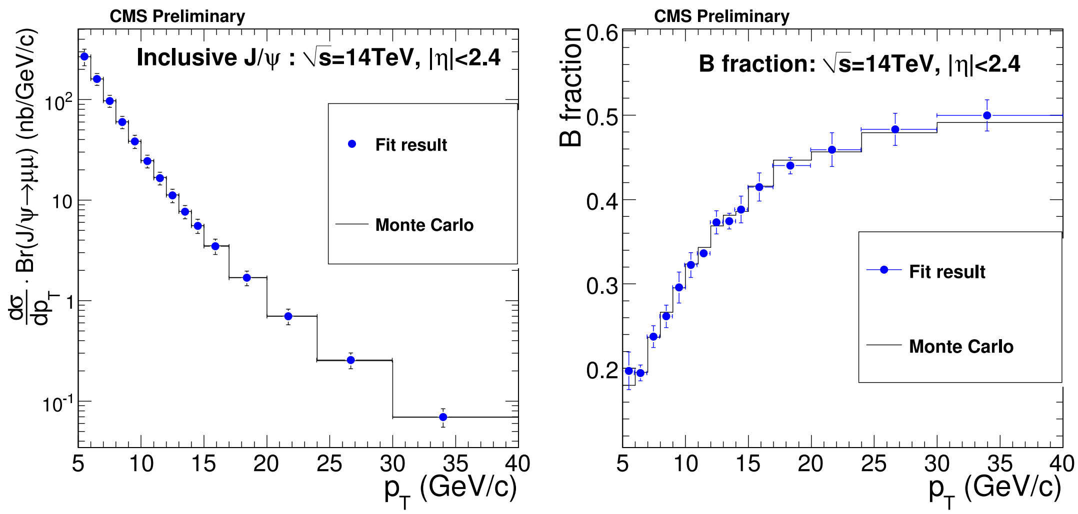

Figure 2: Left: The inclusive J/ψ differential cross section, $d\sigma/dp_T \cdot Br(J/\psi \rightarrow \mu^+\mu^-)$, as a function of the J/ψ transverse momentum, integrated over the pseudorapidity range $|\eta| < 2.4$, corresponding to an integrated luminosity of 3 pb^{-1}. Right: The fitted fraction of J/ψ's from B-hadron decays, as a function of the transverse momentum.

between the vertex of the two muons and the primary vertex of the event, and $m(J/\psi)$ is the J/ψ invariant mass. Already with a small integrated luminosity of the order of 3 pb^{-1}, the precision of the result is limited by systematic uncertainties, and is around 15 %, where the largest systematic uncertainties are on the luminosity measurement (10%), the dependence on the J/ψ polarization (2-7%) and the fit technique (1-6%). Fig. 2 displays the inclusive J/ψ differential cross sections, with combined systematic and statistical uncertainties, corresponding to an integrated luminosity of 3 pb^{-1}. The same figure also shows the result of the fits to the fraction of J/ψ's from B-hadron decay in each bin of transverse momentum.

The uncertainty on the J/ψ polarization can be reduced with a direct measurement of the angular distributions of the muons produced in the J/ψ decay. ATLAS aims to measure the polarization of prompt vector quarkonium states with the first $\mathscr{O}$(10 pb^{-1}), in the transverse momentum range up to 50 GeV/c and beyond. The promptly produced J/ψ mesons and those that originated from B-hadron decays can be separated using the displaced decay vertices, as explained above. With a high production rate of quarkonia at LHC, it will be possible to achieve a higher degree of purity of prompt J/ψ in the analyzed sample and reduce the depolarising effect from B-decays, while retaining high statistics.

A large fraction of prompt J/ψ is produced indirectly through, for example, radiative decays of the χ_c. This feed-down may lead to a different spin alignment and hence to a possible effective depolarization which is hard to estimate. ATLAS aims to measure the rate production of the χ_c by associating a reconstructed J/ψ with the photon emitted from the χ_c decay. The $\mu\mu\gamma$ system is considered to be a χ_c candidate if the difference ΔM between the invariant masses of the $\mu\mu\gamma$ and $\mu\mu$ systems lies between 200 and 700 MeV/c^2, and the cosine of the opening angle α between the J/ψ and γ momenta is larger than 0.97. Fig. 2 shows the distribution in ΔM for the selected χ_c decay candidates. The expected mean positions of the peaks corresponding to χ_0 ,χ_1 and χ_2 signals

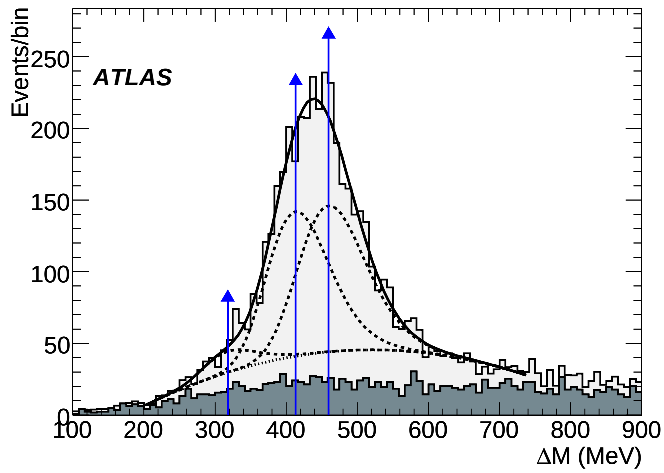

Figure 3: Difference in invariant masses of $\mu\mu\gamma$ and $\mu\mu$ systems in prompt J/ψevents (light grey) with $b\bar{b}$ background surviving cuts (dark grey). The arrows represent the true signal peak positions, and the lines show the results of the fit described in the text. Event yields correspond to an integrated luminosity of 10 pb^{-1}.

(318, 412 and 460 MeV/c^2, respectively) are indicated by arrows. The grey histogram shows the contribution from the background process of J/ψ production from B-hadron decays. The solid line in Fig. 2 is the result of a simultaneous fit to the measured distribution, with the three peak positions fixed at their expected values, and a common resolution.

5. Exclusive B Decays

The exclusive $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ decay can be measured during the initial luminosity phase of the LHC because of the clear event topology and rather large branching ratio. The large $pp \to b\bar{b}$ production rate allows for the measurement of exclusive b production cross-section which have different systematic uncertainties and model dependencies (fragmentation models) from the inclusive ones. The study of these decays can serve as a reference channel for rare B decay searches, whose total and differential cross-sections will be measured relative to their cross-sections, thus allowing the cancelation of common systematic uncertainties. Furthermore, they can be used to estimate the systematic uncertainties and efficiencies of flavor-tagging algorithms that are needed for CP violation measurements. Finally, the relatively large statistics for these decays allow for initial detector performance studies. In particular, the precise measurement of the well-known mass and lifetime [18] can be used for inner detector calibration and alignment studies.

For ATLAS, the reconstruction of $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ starts by forming $J/\psi \to \mu^+\mu^-$ candidates from pairs of oppositely charged muon tracks passing the cuts $p_T > 4$ GeV$/c$ and $|\eta| < 2.4$. Pairs containing at least one muon track with $p_T > 6$ GeV$/c$ were fitted to a common vertex. Pairs are assumed to be muons from J/ψ decays if the vertex fit has $\chi^2/\mathrm{ndf} < 6$ and the invariant mass of the muon pair falls within a 3σ window around the nominal J/ψ mass, with σ =

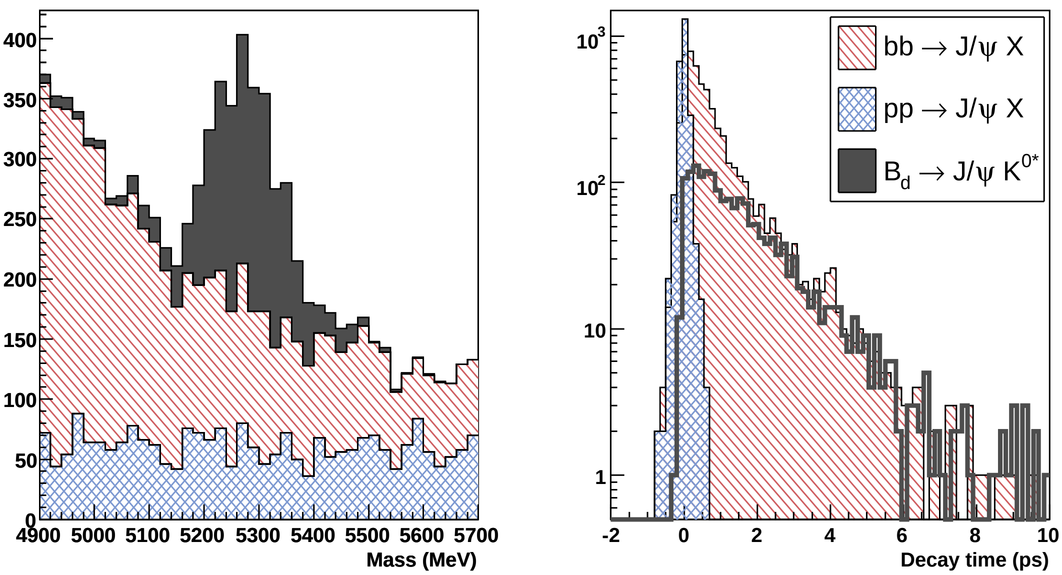

Figure 4: Distributions of the reconstructed B^0 mass and decay time expected with an integrated luminosity of 10 pb^{-1}.

58 MeV. Kaon candidates are chosen among the charged tracks (excluding those already denoted as muons) with $p_T > 1.5$ GeV$/c$ and $|\eta| < 2.7$. Candidate $K^{*0} \to K^{\pm}\pi^{\mp}$ decays are reconstructed by selecting all tracks that have $p_T >$0.5 GeV$/c$ and $|\eta| < 2.5$ that have not been previously identified as muons, forming them into oppositely charged pairs and fitting them to a common vertex. These pairs are assumed to be $K\pi$ from K^{*0} decays if the fit has a $\chi^2/\mathrm{ndf} < 6$, the transverse momentum of the K^{*0} candidate is greater than 3 GeV$/c$, and the invariant mass of the track pair falls within the interval 790-990 MeV$/c^2$, under the assumption that they were left by $K^{\pm}\pi^{\mp}$ hadrons. As an example, we show in Fig. 4 the distributions of the reconstructed B^0 mass and lifetime.

The differential $d\sigma(B^{+,0})/dp_T$ production cross-section can be obtained by a 1-d fit to the reconstructed $B^{+,0}$ invariant masses in different p_T intervals, and the $B^{+,0}$ lifetime can be measured i.e. by a 2-d fit to the B invariant mass and pseudo-proper lifetime. ATLAS aims to an accuracy of about 9-12% on the differential cross-section and the B lifetimes with an integrated luminosity of about 10 pb^{-1}. Since this presentation at FPCP, a new study from CMS on exclusive B decays has been approved [19]. The reconstruction of the two exclusive decays is similar to the one described above. The differential $d\sigma(B^{+,0})/dp_T$ production cross-section and the $B^{+,0}$ lifetimes are obtained by a 2-d fit to the reconstructed $B^{+,0}$ invariant mass and pseudo-proper lifetime distributions. CMS aims to an accuracy of about 10% on the differential cross-section and of 5% on the B^+/B^0 lifetime ratio with an integrated luminosity of about 10 pb^{-1}.

6. Measurement of the Azimuthal Correlation in $b\bar{b}$ Production

The study of $b\bar{b}$ correlations is an important test of the effective contributions from higher-order QCD processes to the b quark production that can be performed with the very first data collected by CMS [20]. Previous measurements of azimuthal correlation distributions at the Tevatron generally agree with the shape predicted by NLO calculations, but not in the normalization [11]. Measurements of $b\bar{b}$ production at the LHC will provide a fundamental test of the QCD predictions in a new energy regime and with much higher statistics. The CMS experiment aims to measure the total $b\bar{b}$ cross section and the differential cross section $d\sigma/d\Delta\phi$ with respect to the opening angle between the two b quarks with the first 50 pb^{-1} of collision data at $\sqrt{s} = 10\,\mathrm{TeV}$. The presence of b quark decays is detected entirely through muonic signatures. The decay of one b is tagged by reconstructing the decay $J/\psi \to \mu^+\mu^-$. Events are also required to contain an additional muon consistent with the semileptonic decay of the second b. This approach is characterized by lower yields with respect to b-quark identification through jet signatures, but it retains the highest sensitivity for $b\bar{b}$ production at small opening angles where NLO processes dominate. The final sample is expected to be characterized by low backgrounds, and is ideal for early data analysis since it does not rely on jets or complicated b-tagging algorithms. In addition, this analysis will be able to provide useful inputs to the detector commissioning regarding the muon reconstruction and identification (in particular on the low p_T region of the spectrum), the trigger efficiency, and the tracker alignment. The main background sources include events with a correctly identified J/ψ and a misidentified muon (a hadron misidentified as a muon, e.g. punch-through hadrons, or real muons from pion or kaon decays-in-flight), events with a correctly identified J/ψ that comes from the primary vertex, and events with a fake J/ψ candidate, where one or both the muons are not coming from the J/ψ decay. The event reconstruction starts by building J/ψ candidates by vertexing every pair of muon candidates with opposite electric charge. The vertexing is required to be successful and the best J/ψ candidate event by event is selected as the one with the highest vertex probability. A third muon in the event is then requested; in case of more than one reconstructed additional muon candidate, the one with the highest p_T is chosen. All three muons in the event must have $p_T > 3$ GeV/c and $|\eta| < 2.4$. The yield in each of eight $\Delta\phi$ intervals is measured using a simultaneous unbinned maximum-likelihood fit to the J/ψ invariant mass, the transverse flight length L_{xy} of the J/ψ, defined as the distance in the x-y plane between the primary vertex and the common vertex of the J/ψ dimuon pair, and the impact parameter d_{xy} of the third muon in the event. Since the size of each $\Delta\phi$ bin is comparable to the measured resolution, an unfolding procedure is necessary to correct the reconstructed $\Delta\phi$ distribution back to the original b quarks. Fig. 5 shows the fit results for a typical sample, corresponding to an integrated luminosity of about 13 pb^{-1}.

The azimuthal correlation distribution is obtained from the signal yields in the different $\Delta\phi$ intervals after correcting for detector effects, such as the limited acceptance, through an unfolding procedure [21]. In Fig. 6 we show the comparison between the generated and unfolded $\Delta\phi$ distributions. Depending on the particular $\Delta\phi$ bin, for an integrated luminosity of about 50 pb^{-1}, an accuracy of 15-25% on the differential cross-section can be obtained, combining statistical and systematic uncertainty. An accuracy at the 10% level is expected for the integrated $\sigma(pp \to b\bar{b})$ total cross section.

7. Search for the Rare Decay $B_s^0 \to \mu^+\mu^-$

The rare decay $B_s^0 \to \mu^+\mu^-$ is mediated by flavor-changing neutral currents that are forbidden in the Standard Model at tree level. The lowest-order contributions in the Standard Model involve

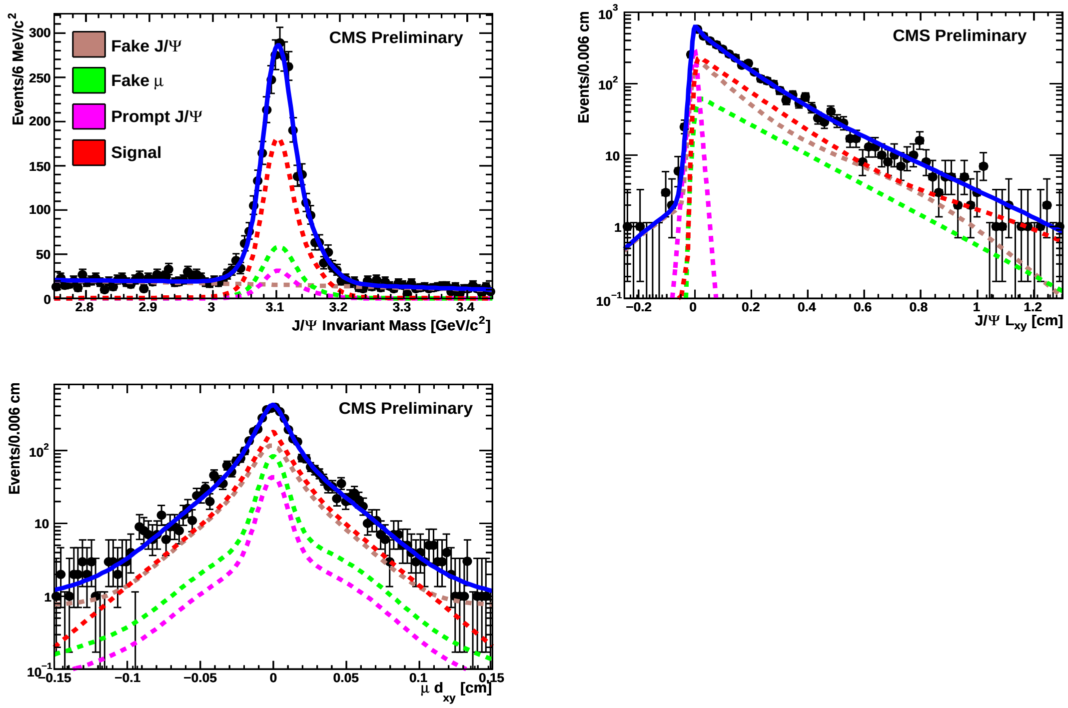

Figure 5: Results of the three-dimensional fit for a typical Monte Carlo sample. The Monte Carlo distributions (points with error bars) a re compared to the results of the overall fit (solid line, blue color). The PDFs for the different fit components are shown in different colors.

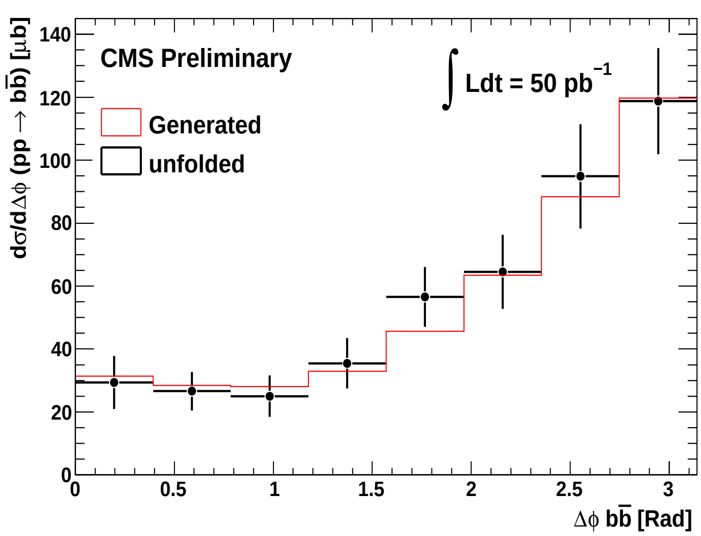

Figure 6: Differential cross section measurement $d\sigma/d\Delta\phi$ after unfolding and including systematic uncertainties.

weak penguin loops and weak box diagrams that are CKM suppressed. In extensions of the Standard Model, the $B_s^0 \to \mu^+\mu^-$ branching fraction may be enhanced by several orders of magnitude. Thus, several experiments have searched for these decays. The largest B_s^0 samples have been collected by CDF and D0 corresponding to a luminosity of 2 fb^{-1} but no signal has been observed. The lowest branching fraction upper limit was set recently by CDF yielding $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ @ 95% confidence level [22]. The reconstruction for this decay is similar for ATLAS and CMS. In di-muon triggered events, pair of oppositely charged muons are selected, and required to pass offline quality cuts (displaced $\mu^+\mu^-$ vertex, isolation with respect other tracks, invariant mass compatible with an B_s^0 candidate). Once recorded data are available, the background in the signal region will be estimated using sidebands in the distribution of the muon pair invariant mass. In the current studies the background was estimated using simulated events, and the background estimate is affected by large uncertanties in the knowledge of the $b\bar{b}$ production cross-section and in the limited Monte Carlo statistics available. After the number of background events in the signal region has been determined, the number of signal events N_B can be determined from a comparison of the total number of events found in the signal region, and the estimated background. For low statistics an upper limit on N_B corresponding to certain confidence level is determined using appropriate statistical methods. Once N_B is determined, the $B_s^0 \to \mu^+\mu^-$ branching fraction can be calculated using a relative normalization, e.g to the reference channel $B^+ \to J/\psi K^+$. While clearly ATLAS and CMS do not expect to observe this decay during the early stages of the LHC, as more luminosity becomes available and the understanding of the backgrounds improves, it should be possible to identify a signal for this process. ATLAS expects a signal of 5.7 events with a background of 14^{+13}_{-10} events for an integrated luminosity of 10 fb^{-1}. CMS [23] expects a signal of 2.4 events with a background of 6.5 ± 2.4 events for an integrated luminosity of 1 fb^{-1}, corresponding to an upper limit of about 1.6×10^{-8} @ 90% confidence level.

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