

MEASUREMENT OF HEAVY-FLAVOR PROPERTIES AT CMS AND ATLAS

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Thanks to the excellent performances of ATLAS and CMS in triggering on muon signals and reconstructing these particles down to low transverse momentum, large samples of heavy-flavored hadrons have been collected in the 2011 LHC run at $\sqrt{s} = 7$ TeV. The analysis of these samples has enabled both experiments to perform competitive measurements of heavy-flavor properties, such as quarkonium polarization, lifetime and CP -violation measurements, hadron spectroscopy and branching ratios of rare B decays.

ATLAS and CMS capabilities in heavy-flavor physics are almost entirely based on muon and di-muon triggers, which can collect signals down to low transverse momenta (typical values for thresholds range between 3 and 6 GeV/ c), while maintaining a reasonable background rate by using high-level selection criteria. Muons are reconstructed offline using techniques which match information from the inner tracking detectors and the muon chambers, and are combined to reconstructed charged tracks to form partially and fully reconstructed final states, like for instance $B_s \rightarrow J/\psi\phi$. All analyses presented are based on the data collected by ATLAS and CMS in 2011, at a center-of-mass energy of 7 TeV, which amounts to an integrated luminosity up to 5.0 fb⁻¹.

1 Quarkonium Polarization

Theoretical predictions on quarkonium polarization at production in hadron colliders are still controversial. Calculations in Non-Relativistic QCD (NRQCD) schemes, including the color-octet mechanism, require inputs from experimental data¹ and the effect of feed-down from heavier charmonium states can be significant². Recent results from the CDF experiment³, which use advanced experimental techniques, including a simultaneous determination of all polarization parameters in difference reference frames⁴, indicate that Υ mesons are not significantly polarized at high transverse momentum ($p_T \gg m_\Upsilon$). NRQCD would predict preponderance of transverse polarization.

CMS⁵ performed a measurement of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations in a p_T range of 10-50 GeV/ c and two rapidity bins. The method is based on the construction of posterior probability distributions which depend on the values of the polarization angles $\cos\theta$ and ϕ

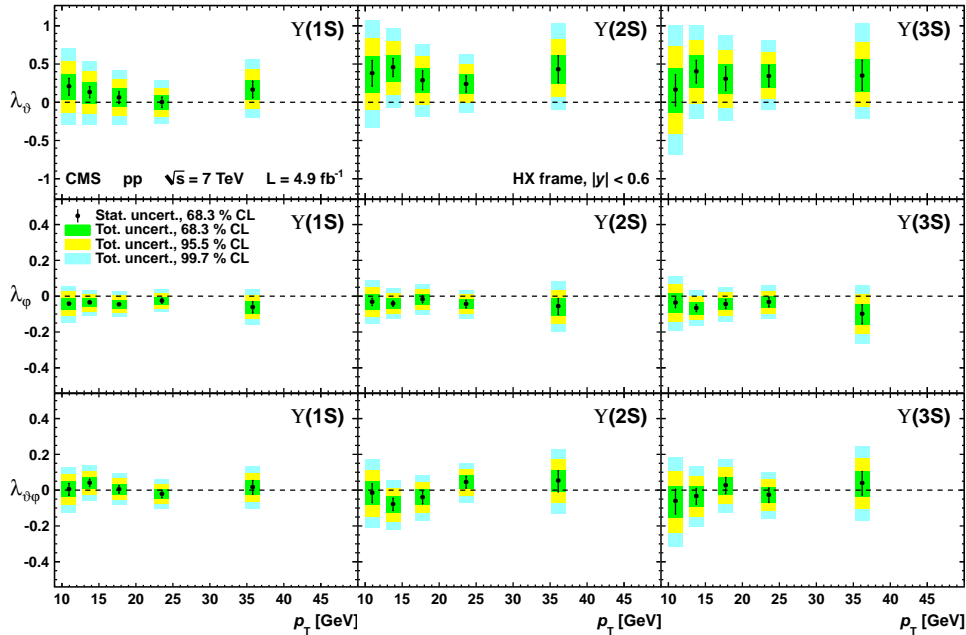


Figure 1: Fitted values of the polarization parameters λ_θ , λ_ϕ , $\lambda_{\theta\phi}$ (rows) in the helicity frame and in the rapidity bin $|y| < 0.6$ for the three states $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ (columns). The notation for uncertainties is explained in the legend.

of reconstructed dimuons and on the reconstruction efficiencies, computed as a function of muon kinematic variables. Background is subtracted using fits to the dimuon invariant mass distributions. Muon efficiencies are extracted from data-driven methods⁶. The result is extracted in several reference frames and the result is cross-checked using frame-independent polarization parameters. Results for the three quarkonium states in the helicity frame are shown in Fig. 1: all of them are compatible with zero within the total uncertainties.

2 Lifetimes and CP violation

B -hadron lifetime values (and lifetime differences in case of oscillating meson systems) represent important tests of Heavy Quark Effective Theory (HQET) and lattice QCD. Experimentally the least known among B -hadron lifetimes is $\tau(\Lambda_b)$: CDF and D0 results are not in agreement⁷ on its measured value and the PDG average value shows a discrepancy with HQET calculations up to order $1/m_b^2$, therefore specific corrections must be introduced to improve the consistency⁸.

ATLAS and CMS⁹ have measured the Λ_b lifetime, with ATLAS also reporting a mass measurement. In both experiments the decay channel $J/\psi\Lambda^0 \rightarrow \mu^+\mu^-p\pi^-$ has been used to reconstruct the Λ_b baryon, profiting from the clean dimuon signature and the displaced decay vertex of the Λ^0 . The mass and lifetime values have been extracted from simultaneous fits to the $J/\psi\Lambda^0$ invariant mass (using mass constraints of the sub-products) and proper decay time distributions. Selection biases have been corrected using simulation. ATLAS obtains: $m(\Lambda_b) = 5619.7 \pm 0.7_{\text{stat.}} \pm 1.1_{\text{syst.}}$ MeV/ c^2 and $\tau(\Lambda_b) = 1.449 \pm 0.036_{\text{stat.}} \pm 0.017_{\text{syst.}}$ ps, while CMS measures $\tau(\Lambda_b) = 1.503 \pm 0.052_{\text{stat.}} \pm 0.031_{\text{syst.}}$ ps. Both results are in better agreement with CDF than with D0 results, although the compatibility between the ATLAS and D0 values is within 1.6σ .

Of particular relevance for the indirect search for New Physics (NP) in processes described by “box” and “loop” diagrams is the measurement of the B_s mixing phase ($\phi_s = -2\beta_s$), whose value in the Standard Model is tightly constrained by precise measurements of quantities related to the unitarity triangle in the B_d system¹⁰. Its value, computed in the Standard Model (SM) hypothesis (only one CP -violating phase) is $\phi_s = -0.0364 \pm 0.0016$ rad. Experimentally the

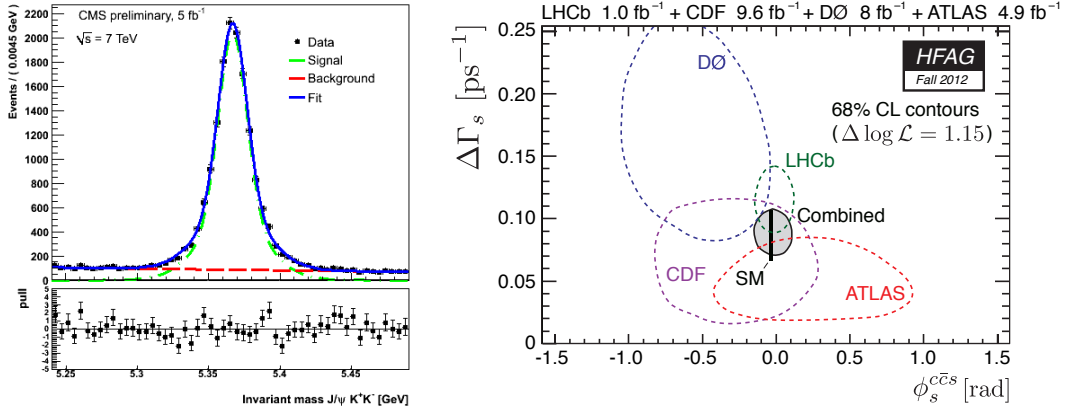


Figure 2: Left: Reconstructed $J/\psi\phi$ invariant mass in CMS with projections of the 5-dimensional fit: colored lines are explained in the legend. Right: Combination of ATLAS, Tevatron and LHCb results in the $\Delta\Gamma_s$ - ϕ_s plane.

measurement can be performed using B_s decays to CP eigenstates. In the results presented here, ATLAS and CMS do not use techniques to identify the flavor of the B_s meson at production and the sensitivity to ϕ_s remains limited. CMS only measured $\Delta\Gamma_s$, fixing ϕ_s to the SM value, while ATLAS has determined both.

ATLAS and CMS¹¹ use the $B_s \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ final state, which is relatively abundant and clean (Fig. 2 left). Because of the entangled CP -even and -odd contributions in the vector-vector meson system, the result is obtained from a five-dimensional fit to B_s mass, proper decay time, and three angular variables related to the distribution in space of the final decay products. The CMS result is $\Delta\Gamma_s = 0.048 \pm 0.024_{\text{stat.}} \pm 0.003_{\text{syst.}} \text{ ps}^{-1}$, while ATLAS measures $\Delta\Gamma_s = 0.053 \pm 0.021_{\text{stat.}} \pm 0.010_{\text{syst.}} \text{ ps}^{-1}$ and $\phi_s = 0.22 \pm 0.41_{\text{stat.}} \pm 0.10_{\text{syst.}}$. While both experiments report values of $\Delta\Gamma_s$ noticeably smaller than the latest high-precision measurement by LHCb¹², this discrepancy is not statistically significant. Fig. 2 right shows the comparison of ATLAS and LHCb results using two-dimensional likelihood contours¹³.

3 Hadron spectroscopy

Theories which explain the formation of hadrons often predict a very large number of states with similar quark structure and different quantum numbers. The quark model predicts baryonic combinations with one or more bottom and charm quarks, many of which have not been observed yet. Similarly, the spectroscopy of $c\bar{c}$, $b\bar{b}$ and $c\bar{b}$ states has been experimentally confirmed in many cases. Still states exist (even below the open-charm and -bottom thresholds) which have never been identified. On the other hand, the existence of a few “unconventional” states, like the $X(3872)$, which are interpreted as bound states but do not fit in the spectroscopy predicted by potential models, has been established.

ATLAS and CMS have performed searches for conventional and exotic hadron states. Using the decay chain $\Xi_b^{0*} \rightarrow \pi^+\Xi_b^- \rightarrow \pi^+J/\psi\Xi^- \rightarrow \pi^+\mu^+\mu^-\pi^-\Lambda^0 \rightarrow \pi^+\mu^+\mu^-\pi^-p\pi^-$, CMS has observed the $J^P = 3/2^+$ partner of the Ξ_b^0 . The presence of three weakly decaying particles in the chain, giving rise to detached vertices, has allowed to isolate a clean signal, as shown in Fig. 3 left. The measured mass is $5945.0 \pm 0.7_{\text{stat.}} \pm 0.3_{\text{syst.}} \pm 2.7_{m(\Xi_b^-)} \text{ MeV}/c^2$, in agreement with theoretical predictions¹⁴. ATLAS reported the first observation of the $\chi_b(3P)$ bottomonium state (actually the superposition of three states with different total spin) using the decay mode $\chi_b(3P) \rightarrow \Upsilon(1S, 2S)\gamma \rightarrow \mu^+\mu^-\gamma$ or $\rightarrow \mu^+\mu^-e^+e^-$, where the photon conversion occurs inside the detector material¹⁵. The signals are shown in Fig. 3 right (for the converted-photon case), and the measured mass is $10530 \pm 5_{\text{stat.}} \pm 9_{\text{syst.}} \text{ MeV}/c^2$. Both observations exceed 6σ significance.

CMS and ATLAS have detected clear signals of $B_c^\pm \rightarrow J/\psi\pi^\pm$ (CMS also reporting evidence

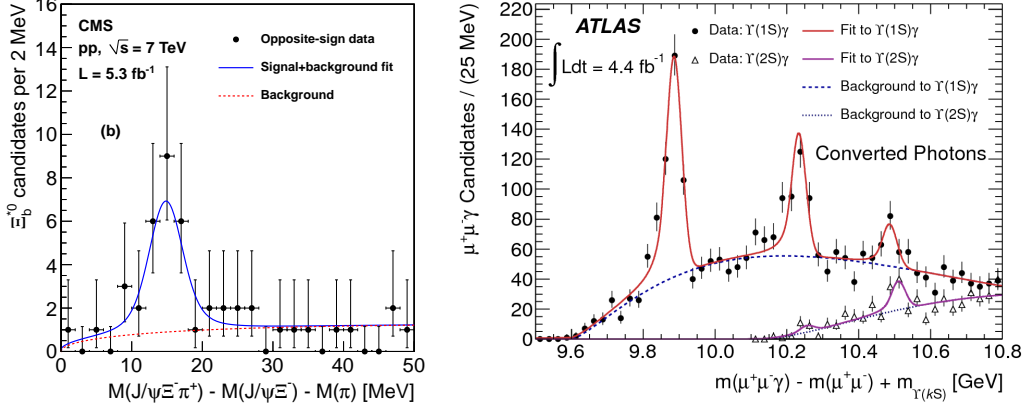


Figure 3: Left: Invariant mass difference (Δm) between the reconstructed $\pi^+\Xi_b^-$ and Ξ_b^- systems in CMS. About 20 events are peaking at $\Delta m \simeq 15$ MeV/ c^2 , indicating a resonant state. Right: $\Upsilon(nS)\gamma$ ($n = 1, 2$) reconstructed invariant mass in ATLAS, fixing the $\Upsilon(nS)$ masses to their PDG values. The rightmost peaks correspond to the newly-observed $\chi_b(3P)$ state.

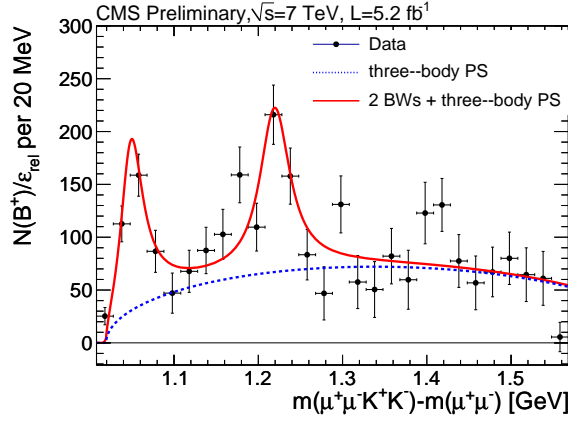


Figure 4: Invariant mass difference (Δm) between the reconstructed $J/\psi\phi$ and J/ψ systems in CMS, obtained with a bin-by-bin background subtraction technique. The distribution is fitted with a phase-space background and two Breit-Wigner shapes convoluted with resolution functions obtained from simulation.

for $B_c^\pm \rightarrow J/\psi\pi^+\pi^-\pi^\pm$) from which cross sections and ratios of branching fractions will be measured. CMS has also investigated possible resonant structures of the $J/\psi\phi$ system in the $B^\pm \rightarrow J/\psi\phi K^\pm$ decay, in order to confirm the CDF observation of a structure at $m_{J/\psi\phi} \simeq 4140$ MeV/ c^2 ¹⁶. As shown in Fig. 4, two structures are clearly seen in the bin-by-bin subtracted invariant mass spectrum of the $J/\psi\phi$ system. Further studies are ongoing in order to understand the exact nature of these structure.

4 Rare B decays

In ATLAS and CMS searches for $B_{d,s} \rightarrow \mu^+\mu^-$ decays have been performed ¹⁷. These decays are predicted to be rare in the SM and a significant enhancement over the SM branching ratios ($\mathcal{B}_{\text{SM}} \sim 10^{-10} - 10^{-9}$ ¹⁸) is possible in most supersymmetric theories ¹⁹. An observation of a non-SM value of the branching fraction would therefore represent an indirect evidence for NP.

In both experiments, a “normalization” sample of events with $B^+ \rightarrow J/\psi K^+$ decays is used to remove uncertainties related to the $b\bar{b}$ production cross section and the integrated luminosity, and to reduce uncertainties on efficiencies, which are determined from simulation. Selection is based on several variables, including high p_T , vertex displacement and dimuon isolation, which have been chosen to mitigate the effects of high pileup. A “blind” analysis approach is applied.

In ATLAS the selection variables are included in a Boosted Decision Tree (BDT), while CMS uses a cut-based selection, and both analyses are optimized for the best upper limit. In CMS, because of better mass resolution, the signal is separated in B_d and B_s regions.

Event-counting experiments are performed in dimuon mass regions around the B_s and B_d masses. Monte Carlo simulations are used to estimate backgrounds due to other rare B decays and combinatorial backgrounds are evaluated from the data in dimuon invariant mass sidebands. In all cases, the observed number of events is consistent with background plus SM signals. In CMS the resulting upper limits on the branching fractions are $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) < 7.7 \times 10^{-9}$ and $\mathcal{B}(B_d \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-9}$ at 95% CL, while ATLAS sets the limit $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) < 2.2 \times 10^{-8}$ at 95% CL. It has been predicted²⁰ by naive luminosity scaling that CMS is expected to observe a SM $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ with more than 3σ significance using the full data set at $\sqrt{s} = 8$ TeV.

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