b-physics with ATLAS and CMS

Louise Oakes, on behalf of the ATLAS and CMS collaborations

Excellence Cluster Universe, Technische Universität München
Boltzmannstr. 2, 85748 Garching, Germany

The ATLAS and CMS b-physics programmes are summarised after nearly two years of data taking. The data were collected in $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC. Results presented include $B$ meson lifetime measurements using 40 pb$^{-1}$ of 2010 data, which demonstrate good agreement with previous measurements, and competitive rare decay studies using the full 2011 data set of up to 5 fb$^{-1}$.

1 Introduction

The LHC provides a rich environment for b-physics studies, having gathered the world’s largest hadron collision samples of $B$ meson decays in the first full year of data taking. The two general purpose detectors, ATLAS$^1$ and CMS$^2$, have b-physics programmes which complement that of the dedicated b-physics experiment LHCb$^3$. This report introduces the wide range of analyses carried out by the ATLAS and CMS b-groups, starting with early measurements which provide an important check of the tracking and calibration of the detectors, to competitive results on rare meson decay channels. Measurements of $B$ hadron production are presented separately$^4$.

2 $B$ meson observations and lifetimes

Both experiments demonstrated with the 2010 datasets of approximately 40 pb$^{-1}$ that $B$ meson lifetimes can be accurately measured with these detectors. This is an important step towards more complex $CP$ violation measurements where the $B$ meson lifetime is a key parameter.

2.1 $B^0_s$ lifetime in $J/\psi \phi$ channel

The channel $B^0_s \to J/\psi \phi$ is known as the golden mode for measuring $CP$ violation in $B_s$ meson decays. ATLAS$^5$ and CMS$^6$ measured the $B$ meson lifetime in this channel to be in good agreement with the world average value$^7$. The background parameterisations used in these analyses can be directly transferred to the $CP$ violation measurement.

ATLAS measures a $B^0_s$ lifetime of $\tau_{B_s} = 1.4 \pm 0.08$ (stat) $\pm 0.05$ (syst) ps in the mode $B^0_s \to J/\psi \phi$. The CMS measurement finds a lifetime of $\tau_{B_s} = 1.59 \pm 0.08$ (stat) ps.

2.2 Inclusive $B$ meson lifetime

The average $B$ meson lifetime, $< \tau_B >$ is measured in $B^0 \to J/\psi X \to \mu^+ \mu^- X$ decays by ATLAS$^8$. Due to the use of partially reconstructed decays, the lifetime is calculated from the
Table 1: CMS expected and observed number of events in the barrel and endcap detector regions for $B^0(s) \rightarrow \mu^+ \mu^-$ pseudo-proper decay time

\[
\tau_B = \frac{L_{xy} \cdot m_{PDG}^{B^0}}{p_T(B)} = \frac{L_{xy} \cdot m_{PDG}^{J/\psi}}{p_T(J/\psi)} \cdot F
\]

where $F$ is a scale factor accounting for the smearing introduced by the use of the $J/\psi$ pseudo-proper decay time, calculated from Monte Carlo weighted to BaBar data. The resulting value is $<\tau_{B_s}> = 1.489 \pm 0.016 \text{ (stat)} \pm 0.043 \text{ (syst)} \text{ ps}$, which is in agreement with the value from the equivalent CDF measurement.9

3 $B^0(s) \rightarrow \mu^+ \mu^-$ searches

The rare decay channels $B^0(s) \rightarrow \mu^+ \mu^-$ provide good tests of physics beyond the Standard Model (SM), as the SM branching ratio is very precisely predicted $^{10}$ $BR(B_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$. Several New Physics theories predict a significant enhancement for this branching ratio. The signature of an opposite sign muon pair whose invariant mass can be precisely measured by the LHC detectors, combined with the clear theory expectations, makes this an ideal channel for beyond the SM searches.

Branching ratios of the rare decays $B^0(s) \rightarrow \mu^+ \mu^-$ are measured relative to a high statistics reference channel, $B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu^+ \mu^-$ or $B_s \rightarrow J/\psi \phi, J/\psi \rightarrow \mu^+ \mu^-$. The main background sources in the $B^0(s) \rightarrow \mu^+ \mu^-$ sample are: 1) Continuum $\mu \mu$, from sequential semi-leptonic and double semi-leptonic decays of heavy flavour hadrons which produce dimuon final states. The level is estimated from data in the $B$ meson mass sidebands. 2) Resonant backgrounds, from misreconstructed two body hadronic decays, where $K$ or $\pi$ mesons in the final state are reconstructed as muons. These contributions are estimated from MC.

The signal is selected by a fully reconstructed decay of a long-lived state, whereas background events are in general partially reconstructed, short-lived decays. The $p_T$ spectrum of decays in the background is generally softer, and a higher track density is expected. These different event topologies are used to select signal like events using a Boosted Decision Tree (BDT) technique or kinematic selection.

3.1 CMS results

CMS has sufficiently fine mass resolution to measure separately the branching ratios of $B^0_s \rightarrow \mu^+ \mu^-$ and $B^0_d \rightarrow \mu^+ \mu^-$. This analysis is based on an integrated luminosity of 5 fb$^{-1}$ and uses two different kinematic selection requirements for the barrel and end cap regions.

Table 1 shows the number of expected and observed events by channel and detector region. The 95% CL upper limits on the branching ratios from CMS are given in the summary table at the end of this section. The p-value for the background only hypothesis for $B^0_s \rightarrow \mu^+ \mu^-$ is 0.06, for the SM signal + background hypothesis the p-value is 0.71.
| Experiment | Channel | Expected | Observed |
|------------|---------|----------|----------|
| LHCb $^{11}$ | $B_s \rightarrow \mu^+\mu^-$ | $7.2 \times 10^{-9}$ | $< 4.5 \times 10^{-9}$ |
| CMS $^{12}$ | $B_s \rightarrow \mu^+\mu^-$ | $8.4 \times 10^{-9}$ | $< 7.7 \times 10^{-9}$ |
| ATLAS $^{13}$ | $B_s \rightarrow \mu^+\mu^-$ | $2.3 \times 10^{-8}$ | $< 2.8 \times 10^{-8}$ |
| LHCb $^{11}$ | $B_d \rightarrow \mu^+\mu^-$ | $1.13 \times 10^{-9}$ | $< 1.03 \times 10^{-9}$ |
| CMS $^{12}$ | $B_d \rightarrow \mu^+\mu^-$ | $1.8 \times 10^{-9}$ | $< 1.7 \times 10^{-9}$ |

Table 2: 95% CL upper limits on branching ratios of $B_{(s)}^0 \rightarrow \mu^+\mu^-$ decays at the LHC

3.2 ATLAS results

ATLAS presents a measurement of the branching ratio for $B_s \rightarrow \mu^+\mu^-$ using a BDT combining kinematic and reconstruction variables for background suppression. The data sample used in this analysis is 2.4 fb$^{-1}$ integrated luminosity taken in 2011.

An important feature of the ATLAS analysis is that the BDT optimisation and background estimation use an independent sample of mass sideband events to avoid bias on the expected limit. The measurement is carried out in 3 different $\eta$ regions, $|\eta| < 1.0, 1.0 < |\eta| < 1.5$, and $1.5 < |\eta| < 2.5$. The number of observed (expected) events in the first $\eta$ region is 2 (5.1), in the second region 1 (0.06) and third region 0 (2.08). The CLs curve at the 95% CL is shown in Figure 1, the upper limit on the branching ratio is given in the summary table.

![Figure 1: (Left CMS $^{12}$, Right ATLAS $^{13}$) 95% CLs(+b) vs branching fraction assuming SM expectations.](image)

3.3 $B_{(s)}^0 \rightarrow \mu^+\mu^-$ results summary

From the previously described measurements, there is no evidence for an anomalous signal. The sensitivity of the analyses is approaching the SM level. Table 2 gives the 95% upper limit on the $B_{(s)}^0 \rightarrow \mu^+\mu^-$ branching ratios from ATLAS and CMS. LHCb results $^{11}$ are also included for comparison.

4 $D^0 \rightarrow \mu^+\mu^-$ decays

The decay $D^0 \rightarrow \mu^+\mu^-$ is a FCNC process, and as such it is heavily suppressed in the SM, with a branching fraction of $10^{-18} - 10^{-13}$. This branching fraction can be enhanced by several orders of magnitude in New Physics models. Searches for FCNC decays in the charm sector are complementary to searches in the $B$ and $K$ meson systems.

CMS carried out a measurement $^{14}$ of the branching fraction of $D^0 \rightarrow \mu^+\mu^-$ with 90 pb$^{-1}$ of 2010 and early 2011 data. The analysis technique is similar to that of the $B_{(s)} \rightarrow \mu^+\mu^-$ measurement, the branching fraction is measured as a ratio with a kinematically similar control mode, in this case a semi-leptonic decay channel is used: $D^{*+} \rightarrow D^0(\mu^+)\pi^+$. Many systematic uncertainties cancel through the use of this ratio. For both the signal and control channels, decays are reconstructed topologically by determining the primary and secondary vertices of the
A $D^0$ candidate is combined with one track from the primary vertex to form the $D^{*+}$. The control channel yields 16458 ± 204 candidates.

The variable $\Delta m = m(D^{*+}) - m(\mu\mu)$ is powerful in selecting $D^0$ signal events, a window of ± 3 MeV around the PDG value is taken. Figure 2 shows the distribution of this variable in the signal and control channels, as well as the dimuon mass distribution in the signal channel. As shown in the figure, in each of the mass and the equally sized side band regions, shown in the figure, a total of 23 events are observed. No evidence for the decay $D^0 \rightarrow \mu^+\mu^-$ is observed. Using the CLs method, the 90% exclusion limit for the branching fraction is calculated as $BR(D^0 \rightarrow \mu^+\mu^-) \leq 5.4 \times 10^{-7}$, which can be compared to the best limit at 95% from LHCb of $BR(D^0 \rightarrow \mu^+\mu^-) \leq 1.3 \times 10^{-8}$.

5 Conclusions

The b-physics programmes of the two general purpose LHC detectors, CMS and ATLAS, have produced a range of competitive results in the first 2 years of data taking at $\sqrt{s} = 7$ TeV. High statistics and good detector performance are the main contributors to these important results. A few highlights in the area of $B$ meson lifetimes and decays have been presented here, heavy flavour production topics are covered in a separate parallel talk. In future, the challenge for b-physics with ATLAS and CMS will be to efficiently use the triggers as LHC luminosity increases. Preliminary studies show that with increasing numbers of primary vertices per event from higher luminosity, the selection efficiency for the analyses presented here will remain fairly constant, meaning that full advantage can be taken of the expected high statistics in 2012 and beyond.

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