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Search for $B_s^0 \to \mu^+\mu^-$ and other exclusive B decays with the ATLAS detector.

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The ATLAS experiment, collecting data in pp collisions at the Large Hadron Collider (LHC), allows a variety of B-physics measurements. In this note we focus on exclusive B decays with $J/\psi \to \mu^+\mu^-$ in the final state and on the search for the decay $B_s^0 \to \mu^+\mu^-$. Using 2.4 fb^{-1} of data collected in the first half of 2011, ATLAS set an upper limit on the branching fraction of $\mathrm{BR}(B_s^0 \to \mu^+\mu^-) < 2.2 \times 10^{-8}$ at 95% confidence level. By combining this result with the corresponding searches with CMS and LHCb detectors the observed number of events is in agreement with the background plus Standard Model signal expectation within 1 σ and the corresponding upper limit to the brancing fraction is 4.2×10^{-9} at 95% CL.

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1. Introduction

The ATLAS experiment [1] has a rich heavy flavour program. In this note we focus on exclusive B hadron decays with $J/\psi \to \mu^+\mu^-$ in the final state, which allow to assess detector performance down to low transverse momentum scales, and on the search for rare $B_s^0 \to \mu^+\mu^-$ decay which provides important constraints to the Standard Model (SM).

Event reconstruction for b-physics measurements is mostly based on precise track reconstruction. A detailed test of these capability was peformed in ATLAS by reconstructing transverse impact parameters of tracks originating mostly from the primary vertex. The trigger for b-physics is based on muon signatures with transverse momentum of few GeV (low-p_T muons). The trigger menus in 2011 were mainly based on di-muon signatures at the first level trigger, and then combined at the higher trigger levels with precise tracking and vertex information.

2. Exclusive B decays

A number of exclusive decays of B mesons with $J/\psi \to \mu^+\mu^-$ in the final state have been observed with the 2010-2011 data collected by ATLAS ($\sim$5 fb^{-1} with a peak instantaneous luminosity of 3.65×10^{33}cm^{-2}s^{-1}). The measurement of the masses and lifetimes of such states provide a precise test of transverse momentum scale calibration in the low-p_T region and a validation of detector alignement and vertexing algotithms. The reconstruction procedure requires two muon candidates originating from the same vertex and with an invariant mass within a given window centered on the J/ψ mass (270, 360 or 480 MeV when 0, 1 or 2 muons have pseudorapidity $\eta > 1.5$). Additional tracks (single pions or kaons or their combination depending to the specific decay) are combined to the J/ψ candidate to fully reconstruct the B hadron.

Figure 1 shows two examples of invariant mass distribution for candidates $B^0 \to J/\psi K^{*0}$ (left) and $B_s^0 \to J/\psi\phi$ (center) obtained with the early data at 7 TeV (40 pb^{-1} in 2010). For the decay

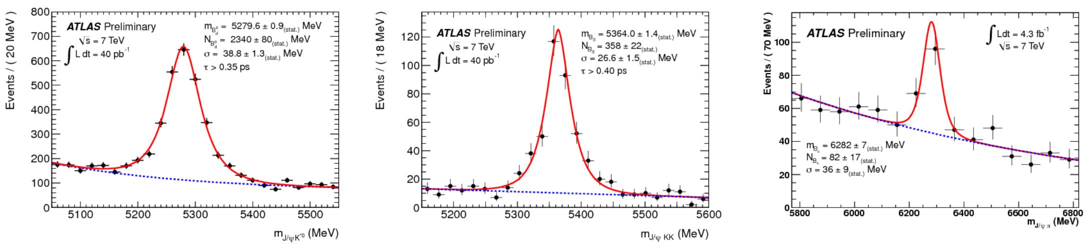

Figure 1: Invariant mass distributions of reconstructed B hadron candidates. The points with error bars are data. The solid line is the projection of the result of the unbinned maximum likelihood fit to all candidates in the signal mass range. The dashed line is the projection for the background component of the same fit. Left: distribution for $B^0 \to J/\psi K^{0*}$ [3]. Center: distribution for $B_s^0 \to J/\psi\phi$ [3]. Right: $B_c^\pm \to J/\psi\pi^\pm$ [4].

of the B^0, the K^{*0} is reconstructed with its decay in $K^\pm\pi^\mp$ by selecting two non-muon opposite charged tracks with p_T >0.5 GeV to which kaon and pion masses are assigned and by requiring their invariant mass to be in the range 847-946 MeV and the transverse momentum of the K^{*0} candidate is greater than 2.5 GeV. A four-tracks vertex fit is applied to the two muons from the J/ψ candidate plus the two additional charged tracks is applied to fit the decay vertex of B^0. For the example given in figure 1, additional cut requesting a proper decay time of a B^0 candidate to be bigger than 0.35 ps was applied. The ϕ from the decay of the B_s^0 is reconstructed with its decay in K^+K^- by selecting two non-muon opposite charged tracks with p_T >1 GeV to which kaon masses are assigned and by requiring their invariant mass to be in the range 1009-1031 MeV. A four-tracks vertex fit is applied to the di-muon candidate plus the two additional charged tracks to fit the decay vertex of B_s^0. Additionally, a proper decay time of B_s^0 candidates was requested to be bigger than 0.40 ps, for the mass distribution shown in figure 1. An advanced ATLAS studies of $B_s^0 \to J/\psi\phi$ decay using ∼4.7 fb^{-1} of 2011 data are presented in a dedicated contribution at the same proceedings [6]. A fit to the mass shapes gives a mass value of (5279.6±0.9) MeV and (5364.0±1.4) respectively for B^0 and B_s^0, in good agreement with the expected values from [2]. Another interesting decay is $B_c^\pm \to J/\psi\pi^\pm \to \mu^+\mu^-\pi^\pm$. B_c (bound state of b and c quarks) represents an useful test for non-relativistic potential models, perturbative QCD and lattice calculation. In this case the di-muon invariant mass is required to be in an interval of ±180 MeV around the J/ψ mass and for the additional charged track the mass hypotesis of a charged pion is applied. The ($J/\psi\pi$) invariant mass, required to be in the range 5770–6820 MeV, is shown in figure 1 right for 4.3 fb^{-1} data collected at 7 TeV; the fit to the mass shape gives the measured value of the $B_c^\pm$ mass of (6282±7) MeV in good agreement with (6277±6) from [2].

3. Search for $B_s^0 \to \mu^+\mu^-$

The exclusive di-muon decay $B_s^0 \to \mu^+\mu^-$ is a flavour-changing neutral-current process forbidden at tree level in the SM. It occurs only via helicity suppressed loop diagrams. The predicted branching fractions for this process is: $BR(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.2\pm0.2)\times10^{-9}$ [5]. The non vanishing decay width difference $\Delta\Gamma_s$ of the B_s^0–$\bar{B}_s^0$ system affects the experimental extraction of the branching fraction. According to [7], to be compared to an experimental value, the previous theoretical prediction should be enlarged by 9%. Theories beyond the SM can significantly enhance these branching fractions [8]. In particular, constrained fits to SUSY models, such as CMSSM and NUHM1, provide expectations for an enhancement of BR($B_s^0 \to \mu^+\mu^-$) of about 20% and 90% respectively [9]. So far neither an enhancement of the branching fractions have been observed nor the SM limits have been reached experimentally.

The first search for $B_s^0 \to \mu^+\mu^-$ with the ATLAS detector [10] was based on 2.4 fb^{-1} of the 2011 data, selected with a di-muon trigger with p_T >4 GeV for both muon candidates.

3.1 Analysis overview

In order to minimize systematic uncertainties due to luminosity measurement and to $b\bar{b}$ production, the $B_s^0 \to \mu^+\mu^-$ branching fraction is measured with respect to the reference channel $B^\pm \to J/\psi K^\pm \to \mu^+\mu^-K^\pm$ chosen to have a large production rate and two muons in the final state:

$$BR(B_s^0 \to \mu^+\mu^-) = BR(B^\pm \to J/\psi K^\pm \to \mu\mu K^\pm) \times \frac{f_u}{f_s} \times \frac{\alpha_{J/\psi K^\pm}\cdot\varepsilon_{J/\psi K^\pm}}{\alpha_{B_s\to\mu\mu}\cdot\varepsilon_{B_s\to\mu\mu}} \times \frac{N_{\mu\mu}}{N_{J/\psi K^\pm}} \tag{3.1}$$

The right-hand-side of (3.1) includes: the branching fraction of the reference channel [2]; the relative production cross sections for $B^\pm$ and B_s^0 (f_u/f_s = 0.267±0.021 assuming $f_u = f_d$ [11]

and no p_T or η dependence); acceptance and efficiency ratios estimated from MC samples; event yields.

The signal region, defined as a di-muon invariant mass region of ± 300 MeV around the B_s^0 mass, is excluded from the optimisation of the selection procedure (blind analysis). Instead, the $B_s^0 \to \mu^+\mu^-$ Monte Carlo (MC) signal and the background extrapolated from sidebands, (4766–5066) MeV and (5666–5966 MeV), are used. To avoid any bias in the optimisation procedure, the data sample is split into two parts: one half of the data is used for the selection optimisation and another half for the background measurement. The number of signal candidates $N_{\mu^+\mu^-}$ is counted after unblinding. The yield $N_{J/\psi K^\pm}$ is measured from data with a maximum likelihood fit on the selected events (see Figure 2 left), assessing the systematic uncertainties by varying the bin size, the signal and background fit models and by inclusion of the per-event mass resolution into the fit. The upper limit is extracted with the modified frequentist (CLs) method [12]. The mass resolution of the ATLAS detector depends on the pseudo-rapidity η of the reconstructed particles. Therefore the data sample was split into 3 mass resolution categories defined by $|\eta_{max}|$ of the two muons: 0–1 (60 MeV resolution), 1–1.5 (80 MeV) and 1.5–2.5 (110 MeV). The event selection was optimised separately for each category and the results are combined within the CLs method.

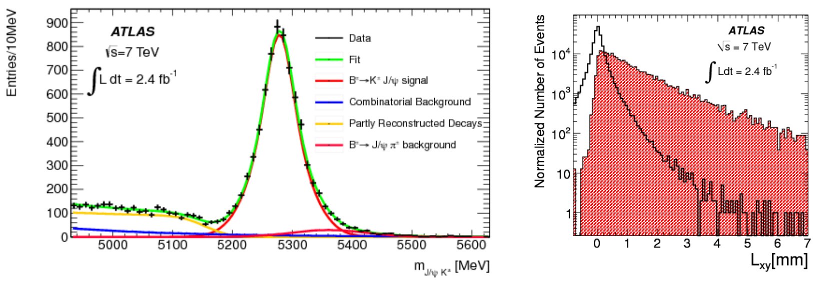

Figure 2: Left: $J/\psi K^\pm$ mass distribution for $B^\pm$ candidates [10]. Curves correspond to the fit components: two Gaussians with a common mean for the main peak, a single Gaussian with higher mean for the $B^\pm \to J/\psi\pi^\pm$ decay, a falling exponential for the continuum background and an exponential function multiplying a complementary error function for the partially reconstructed decays. Right: MC signal (filled histogram) and sideband (empty histogram) distributions for the L_{xy} variables described in the text for $B_s^0 \to \mu^+\mu^-$ [10].

3.2 Background composition and signal selection

The background has continuous and resonant components. The continuous background originates from the random combination of muon tracks created in $q\bar{q}$ annihilation processes which could be of prompt (e.g. Drell-Yan) or of non-prompt (dominated by $b\bar{b} \to \mu^+\mu^- X$ decays) origin. The resonant background comes from the decays of neutral B mesons with one ($B \to K\mu\nu$) or two hadrons ($B \to hh$ like $B_{(s)} \to \pi\pi, KK, \pi K$) in the final state, for which one or both hadrons are mis-identified as muons, mainly due to hadron punch-through or to in-flight decays. The resonant background mimics the signal topology and therefore is hard to suppress; its contribution was estimated from dedicated MC samples using data-driven mis-identification rates.

For the selection of the B_s^0 candidates out of the continuum background, 14 discriminating variables were identified as inputs for the multi-variate analysis [10]. The most discriminating variables are: the distance of the B_s^0 decay (secondary) vertex from the primary vertex, the proper time significance, the pointing angle, the isolation of the di-muon tracks and the transverse momentum of the B_s^0. As an example the distributions for signal MC and sideband data for the distance between primary and secondary vertex in the transverse plane (L_{xy}) are shown in figure 2 right. The discriminating variables are used to train a Boosted Decision Trees (BDT) in the TMVA package [13]. The BDT selection and the size of the mass search window have been optimised in each mass resolution category by maximising the estimator $P = \frac{\varepsilon_{sig}}{1+\sqrt{N_{bkg}}}$ for 95% CL [14], where ε_{sig} is the signal selection efficiency and N_{bkg} is the number of background events in the search region.

3.3 Results and LHC combination

The inputs to the limit extraction are the observed number of events in the 3 resolution regions (2/1/0); the events observed in the half of the sideband region (5/0/2), giving a total of 6.1 events expected in the signal region; the contribution of the resonant background (0.24 events in total). The expected limit is calculated prior to unblinding in the background-only hypothesis and is found

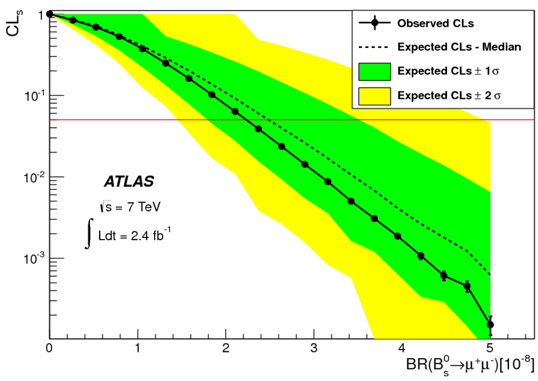

Figure 3: Observed CLs (circles) as a function of BR($B_s^0 \to \mu^+\mu^-$) with the ATLAS experiment. The 95% CL limit is indicated by the horizontal line. The dark (green) and light (yellow) bands correspond to $\pm 1\ \sigma$ and $\pm 2\ \sigma$ fluctuations on the expectation (dashed line) [10].

to be $2.3^{+1.0}_{-0.5} \times 10^{-8}$ at 95% CL. The corrsponding observed limit is 2.2×10^{-8} at 95% CL [10], shown in figure 3. No excess of events was found with respect to the background expectations.

The ATLAS analysis has been combined with the equivalent analysis of the CMS [15] and LHCb [16] experiments. Figure 4 shows the result of the combination procedure [17]: the observed upper limit to the brancing fraction is 4.2×10^{-9} at 95% CL. The combined number of observed event is compatible with the expected background plus a SM signal within 1 σ (1-CL_{s+b}=84%) (fig. 4 left), while the p-value of the background-only hypotesis is 1-CL_b=5% (fig. 4 right).

4. Conclusion

ATLAS has a rich B-physics program. Reconstruction of exclusive B mesons decays with a J/ψ decaying into two muons is a valuable way for assessing detector and trigger performance down to low transverse momentum scales. In addition high statistics of exclusive B decays with a J/ψ collected by ATLAS in 2011 allowed several competitive measurements in this field. ATLAS

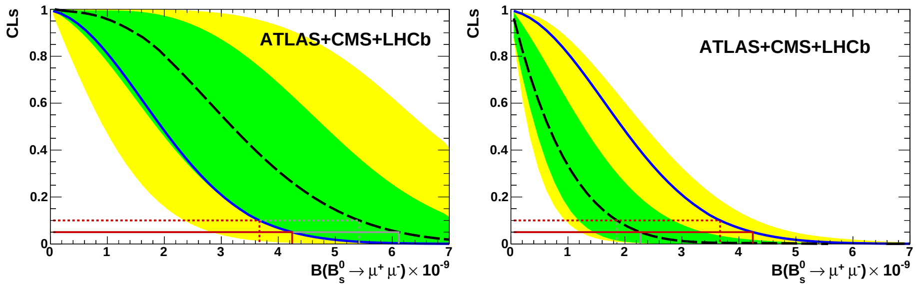

Figure 4: Observed CLs (continuous line) as a function of BR($B_s^0 \to \mu^+\mu^-$) with the ATLAS+CMS+LHCb experiments. The 95% CL limit is indicated by the horizontal (red) line. The dark (green) and light (yellow) bands correspond to $\pm 1\ \sigma$ and $\pm 2\ \sigma$ fluctuations on the expectation (dashed line) for background and 1 SM signal (left plot) and background-only (right plot). Both plots are from [17].

has also performed a search for the rare $B_s^0 \to \mu^+\mu^-$ decay with 2.4 fb^{-1} data collected in 2011 and set an upper limit to the branching fraction of 2.2×10^{-8} at 95% CL. This result was combined with the equivalent results from CMS and LHCb Collaborations, giving the most stringent limit on the branching fractio: BR($B_s^0 \to \mu^+\mu^-$) $< 4.2 \times 10^{-9}$ at 95% CL. The observed number of events is compatible with expectations from background plus SM signal within 1σ, while is compatible with the background-only hypotesis at 5% level.

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