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Measurement of B_s^0 effective lifetime in $\mu^+\mu^-$ decay with the ATLAS detector at the LHC

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Summary. — A study on the measurement of the effective lifetime of the B_s^0 meson in its $\mu^+\mu^-$ decay channel has been performed using simulated samples corresponding to the dataset collected at $\sqrt{s} = 13\,\text{TeV}$ in 2015–2016 by the ATLAS experiment. This quantity has never been measured by the ATLAS Collaboration. A Boosted Decision Tree (BDT) multivariate discriminant has been used to improve the discrimination of the signal over the combinatorial di-muon background. First, an optimisation of the BDT working point has been studied, to maximise the significance of the signal over the background, then a fit model has been developed to extract the effective lifetime. The expected statistical uncertainty on the lifetime was found to be 0.38 ps and a first estimate of the systematic uncertainty on the fit model was evaluated to be 0.1 ps.

1. – Introduction

1˙1. *b-quark and B-mesons.* – Many models of new physics have been proposed to address questions that are still unresolved, but no evidence has yet been observed of dynamics or particles that go beyond the Standard Model (SM) at the LHC [1]. A peculiar role in this framework is played by the b-quark, as the t-quark weak doublet partner in the third quarks generation. The existence of the third-generation quark doublet was proposed in 1973 by Kobayashi and Maskawa [2] in their model of quark mixing matrix (the "CKM" matrix) and confirmed four years later by the first observation of the $b\bar{b}$ meson [3]. Since the b-quark is the lightest member of the third generation quark doublet, the decays of b-flavoured hadrons occur via flavour-changing processes parametrised through this matrix. However, because of confinement, b-quarks can be found only as bound states with null color charge configuration, such as the ones composed of a quark-antiquark pair (mesons) or three quarks (baryons). B-mesons are bound states of a b-quark with up, down, strange or charm quarks. The measurement of B^0 and B_s^0 lifetimes allows the determination of CKM matrix coefficients. One of the consequences of the flavour structure and symmetries of the SM is that certain processes that would be kinematically allowed are instead strongly suppressed. One of the more interesting examples of this suppression is related to a class of process mediated by “Flavour Changing Neutral Currents” (FCNC). Due to the structure of the electroweak lagrangian, any transition between quarks with the same electric charge but belonging to a different weak isospin doublet is suppressed as it can proceed only through loop diagrams. Among these processes, the fully leptonic B-meson decays offer excellent opportunities to test the SM precisely, because of minimal hadronic uncertainties in theoretical predictions. In particular, the decays of B^0 and B_s^0 in a muon-antimuon pair are the ideal place to perform such tests given their very clean signature, even in a complicated environment such as the outcome of pp collisions at the LHC. In the SM, the $B_{(s)}^0 \to \mu^+\mu^-$ decays are affected by loop, helicity and CKM matrix elements (V_{ts} and V_{td}) suppressions. The smallness and precision of the $B_{(s)}^0$ predicted branching fractions provide a favourable environment for observing contributions from new physics processes: any significant deviation could be a hint of new phenomena. The combination of results from the ATLAS [4], CMS [5] and LHCb [6] Collaborations using data collected in the 2011–2016 data taking campaigns gives $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$ and an upper limit of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.6(1.9) \times 10^{-10}$ at 90% (95%) CL [7].

1·2. *The lifetime measurement.* – The B_s^0 effective lifetime measurement is a complementary probe to the branching fraction measurement in the search of new physics beyond the SM. It is important because it allows disentangling the contributions from the two eigenstates of the B_s^0-$\bar{B}_s^0$ system. The relation

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left(\frac{1+A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right) \tag{1}$$

holds, where $\tau_{B_s^0} = 1.510 \pm 0.005\,\mathrm{ps}$ is the B_s^0 mean lifetime, $y_s = \Delta\Gamma/(2\Gamma)$ [6]. The $\Delta\Gamma$ value is the difference between the decay widths of light and heavy mass eigenstates. Since in the SM only the CP-odd (“heavy” eigenstate) contributes to the $B_s^0 \to \mu^+\mu^-$ transition, the $A_{\Delta\Gamma}$ value is predicted to be exactly 1. This does not necessarily hold in new physics scenarios. Experimentally $\tau_{\mu^+\mu^-}$ measured as the exponential decay constant in the distribution of the pseudo-proper decay time is defined as

$$t = \frac{L_{xy} m_B}{c|\vec{p}_B|} \tag{2}$$

This distribution can be measured experimentally, thus allowing the extraction of $\tau_{\mu^+\mu^-}$. The B_s^0 effective lifetime has been measured by the LHCb and CMS Collaborations. The combined result was $\tau_{\mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\,\mathrm{ps}$ [7]. The $B_s^0 \to \mu^+\mu^-$ effective lifetime has not been measured by the ATLAS Collaboration yet.

2. – Analysis strategy

The B_s^0 candidates selection follows the one used by the ATLAS Collaboration to measure the $BR(B_{(s)}^0 \to \mu^+\mu^-)$ [8]. B_s^0 candidates are built from two oppositely-charged muons with transverse momentum of at least 4 GeV and 6 GeV. In this study, only MC samples have been used. The signal region is simply defined by the range $5166\,\mathrm{MeV} < m_{\mu^+\mu^-} < 5526\,\mathrm{MeV}$ where $m_{\mu^+\mu^-}$ is the di-muon pair invariant mass.

2·1. *Effective lifetime measurement.* – The $B_s^0 \to \mu^+\mu^-$ effective lifetime was extracted from a fit to the pseudo-proper decay time t (see eq. (2)) from simulated signal candidates whose invariant mass falls in the signal region. A maximum likelihood fit to the di-muon invariant mass distribution has then been performed using the model

$$f(t) = N_1 e^{\frac{-(t-\mu)^2}{\sigma^2}} * N_2 e^{-at} Erf(a_1 t) \quad (3)$$

where the error function accounts for effects due to selection cuts and the Gaussian component models experimental resolution effects.

2·2. *Background composition.* – Real muon pairs are one of the primary background sources in this analysis [8]. The dominant background in the signal region is the so called "continuum background" which is made of real di-muon pairs originating from the decay chain of b-quarks in a $b\bar{b}$ pair production process and passing all selections needed to form a possible B_s^0 candidate. Other sources of background listed in [8] are neglected for this study.

2·3. *BDT optimisation studies.* – A Boosted Decision Tree (BDT) has been developed in [8]: it combines information from 15 physical input variables to discriminate between the signal and the "continuum background". These variables are related to the B_s^0 meson kinematics, the muons kinematics and properties of the remainder of the pp collision [8]. A single lower cut on the BDT output is exploited for the lifetime measurement. This selection is optimised for the best analysis performance by aiming for the best signal significance, defined as $A = S/\sqrt{(S+B)}$. S and B are the MC predictions respectively for signal and background yields in the signal region. Real data events from invariant mass sidebands ($4766\,\text{MeV} < m_{\mu^+\mu^-} < 5166\,\text{MeV}$ or $5526\,\text{MeV} < m_{\mu^+\mu^-} < 5966\,\text{MeV}$) have been used to normalise the background predictions. The signal yield prediction is based on the SM expectation for $BR(B_s^0 \to \mu^+\mu^-)$ and takes into account the analysis efficiencies. The optimal BDT configuration coming from the maximisation of A corresponds to a cut on the BDT output at 0.365. With this configuration, the expected number of events is: $N_s = 50$ for signal events and $N_b = 30$ for background events.

2·4. *Fitting strategy.* – The aim of this study is to estimate the expected statistical uncertainty on the effective $B_s^0 \to \mu^+\mu^-$ lifetime $\tau_{\mu^+\mu^-}$. To do that, the MC signal sample has been divided into five sub-samples, each with arbitrarily generated lifetime value in the range $\tau_L = 1.423\,\text{ps}$–$\tau_H = 1.620\,\text{ps}$ (corresponding to the CP even/odd eigenstates respectively). For each of the five sub-samples, the signal lifetime (and corresponding uncertainty) was extracted from a fit to the proper-time distribution (using eq. (3)). A calibration curve, which relates for each sub-sample the lifetime value used to generate the sample and the fitted lifetime value, was built and used to correct the fitted value of $\tau_{\mu^+\mu^-}$ and its uncertainty. The shift between the generated and the fitted lifetimes was estimated to be 0.1 ps. A sixth sub-sample has been used to generate pseudo-data according to two benchmark lifetime values: $\tau^{(1)}_{\mu^+\mu^-} = 1.450\,\text{ps}$ and $\tau^{(2)}_{\mu^+\mu^-} = 1.600\,\text{ps}$. These benchmark values have been used to produce 1000 pseudo-experiments to estimate the statistical uncertainty on the fitted lifetime $\tau_{\mu^+\mu^-}$. Each pseudo-experiment has been generated with a Poissonian fluctuation of $N_s = 50$ events and has then been fit with eq. (3). Lifetime values for the two benchmark pseudo-datasets have been extracted. To properly assess the statistical uncertainty on the fitted lifetimes, the RMS of the pseudo-experiments residuals has been considered. Then, 10000 pseudo-experiments have been generated for each of the five points of the calibration curve in order to properly propagate the statistical uncertainties on the two fitted lifetimes. The RMS of the residuals obtained after the correction represents the best expected value for the statistical uncertainty on the fitted lifetimes and it was found to be 0.38 ps for both benchmark points. Finally, the systematic uncertainty arising from the fit model assumption has been probed with an alternative model $\hat{f}(t)$ defined as:

$$\hat{f}(t) = N_1 e^{\frac{-(t-\mu)^2}{\sigma^2}} * N_2 e^{-at} Erf(a_1|t-a_2|) \tag{4}$$

The complete procedure described above has been repeated and a shift of 0.05 ps has been found. This value, together with the shift described above and related to the calibration curve, gives a preliminary estimation of the systematic uncertainty of the fit procedure of 0.1 ps.

3. – Conclusions

Purely leptonic B meson decays offer excellent opportunities to perform precision tests of the SM. First studies for the ATLAS measurement of the B_s^0 effective lifetime in the decay $B_s^0 \to \mu^+\mu^-$ have been performed, using simulated samples emulating the dataset collected at $\sqrt{s} = 13$ TeV in 2015–2016 by the ATLAS experiment. First, a selection optimisation has been performed, to maximise the signal significance. The optimal cut for the BDT score was found to be 0.365. Then, a fit model has been studied to extract the effective lifetime $\tau_{\mu^+\mu^-}$ from the proper-time t distribution. The expected statistical uncertainty on $\tau_{\mu^+\mu^-}$ has been estimated to be 0.38 ps. Finally, a first preliminary estimate of the systematic uncertainty on the fit model has been performed and the value obtained is 0.1 ps.

REFERENCES

[1] Lyndon E. and Philip B., *JINST*, **3** (2008) S08001.
[2] Kobayashi M. and Maskawa T., *Prog. Theor. Phys.*, **49** (1973) 652.
[3] Herb W. S. *et al.*, *Phys. Rev. A*, **39** (1977) 252.
[4] ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[5] CMS Collaboration, *Phys. Rev. Lett.*, **111** (2013) 101804.
[6] LHCb Collaboration, *Phys. Rev. Lett.*, **118** (2017) 191801.
[7] ATLAS Collaboration, LHCb Collaboration and CMS Collaboration, *Combination of the ATLAS, CMS and LHCb results on the $B^0_{(s)} \to \mu^+\mu^-$ decays*, in *ATLAS-CONF-2020-049*, `http://cds.cern.ch/record/2728059`.
[8] ATLAS Collaboration, *JHEP*, **04** (2019) 098.