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Searching for physics beyond the Standard Model in the decay $B^+ \to K^+K^+\pi^-$

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Abstract

The observation potential of the decay $B^+ \to K^+K^+\pi^-$ with the ATLAS detector at LHC is described in this paper. In the Standard Model this decay mode is highly suppressed, while in models beyond the Standard Model it could be significantly enhanced. To improve the selection of the $K^+K^+\pi^-$ final state, a charged hadron identification using Time-over-Threshold measurements in the ATLAS Transition Radiation Tracker was developed and used.

1 Introduction

Many B-meson decays have been considered for observing effects originating from physics beyond the Standard Model (SM). In general, the following classes of B decays are most sensitive to new physics effects: 1) Δb=1 processes through penguin diagrams, 2) Δb=2 processes through box diagrams, and 3) tree-level processes mediated by exchange of a new particle.

Processes such as $\mathrm{b} \to \mathrm{s}\gamma$, belonging to the class 1), have been analysed [1], but theoretical uncertainties hamper the observation of new physics signatures [2]. Similar channels such as $\mathrm{b} \to \mathrm{sq\bar{q}}$ [3] and $\mathrm{b} \to \mathrm{s}\ell\bar{\ell}$ [4] also suffer from large theoretical uncertainties. Some other processes such as $\mathrm{B} \to \tau$, representing the class 3), have been shown to be rather insensitive to a large class of new physics models [5].

Rare decays, representing the class 2), can probe efficiently new physics effects, since for these decays the SM typically predicts extremely tiny branching ratios. The process $\mathrm{b} \to \mathrm{ss\bar{d}}$ is a decay which is strongly suppressed in the SM. This decay can be produced in the SM by box diagrams (see Fig. 1a) with an estimated branching ratio at a level lower than 10^{-11}. The Minimal Supersymmetric Standard Model (MSSM) introduces squark-gaugino (or higgsino) box diagrams (see Fig. 1b), increasing the estimated branching ratio to $10^{-7} - 10^{-8}$ [6]. The decay has also been studied in the context of several Two Higgs Doublet Models (THDM) [7]. The studies have shown that in these cases, the branching ratio could be as high as 10^{-7}. Supersymmetry with broken R parity provides another model with a significant enhancement of this decay (see Fig. 1c) [6]. These decays are tree-level processes (class 3) in our classification), and therefore the branching ratio could be even significantly higher than those predicted for the box-diagram processes.

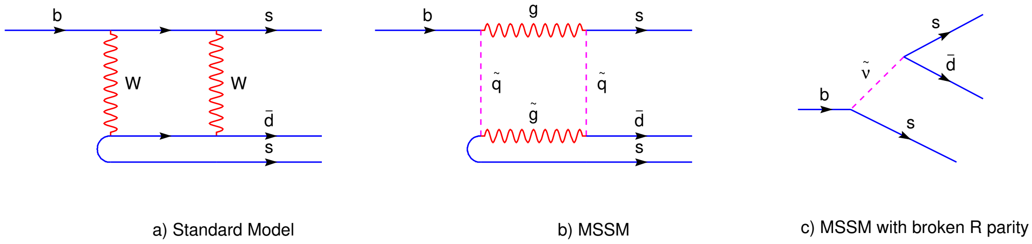

Figure 1: Feynman diagram contributions to the decay $\mathrm{b} \to \mathrm{ss\bar{d}}$ in various models: a) The Standard Model, b) MSSM, c) MSSM with broken R parity.

Three-body decays of a charged B, such as $B^{\pm} \to K^{\pm}K^{\pm}\pi^{\mp}$ (either directly or through a K*-resonance), were suggested as a clear signal for the process $b \to ss\bar{d}$ in Ref. [6]. Recently, an upper limit of $8.79 \cdot 10^{-5}$ was set by the OPAL collaboration for the branching ratio $BR(B^{\pm} \to K^{\pm}K^{\pm}\pi^{\mp})$ at 90% confidence level [8].

In this paper, the direct decay $B^{+} \to K^{+}K^{+}\pi^{-}$ was considered [1] in order to test the feasibility of observing these decays in the ATLAS experiment at the Large Hadron Collider (LHC). Similar analysis could be performed with a more general class of final states $B^{\pm} \to K^{\pm}K^{\pm}$ + (no strange), including also K*-resonances, to increase the statistics. In sections 2-4 the analysis procedure and simulation results for ATLAS are described. In section 5 the reach of other experiments is estimated, and section 6 summarises the paper.

2 Event simulation

The $B^{+} \to K^{+}K^{+}\pi^{-}$ decay was implemented in the Monte Carlo program PYTHIA 5.7 [9] in order to generate the signal sample. In the event generation, b-quark pairs were produced in pp-collisions at $\sqrt{s} = 14$ TeV either directly via the lowest order process, or via gluon splitting or flavour excitation.

Events containing a B^{+} meson were selected, and then the B^{+} was forced to decay into a $K^{+}K^{+}\pi^{-}$ final state. The associated $\bar{b}$ was forced to decay semileptonically into μX, in order to satisfy the ATLAS level-1 trigger requirements for B hadrons (a muon with a $p_T > 6$ GeV and $|\eta| < 2.4$)[2]. The muon was not needed in the subsequent analysis as such.

The ATLAS second level trigger for this hadronic B decay could be envisaged to be the presence of three charged particles with $p_T > 1.5$ GeV, forming an invariant mass close to the B-meson mass. The detailed trigger rates have not been studied.

For this feasibility study, a fast simulation program was used instead of a full GEANT simulation. The parametrisation was established by studying in detail the resolutions of the five helix parameters of the tracks in fully-simulated samples, including tails ([10],[11]). The smeared five helix parameters of the track and the corresponding covariance matrix were obtained, and a look-up table as a function of p_T and η was produced. The parametrisation was then applied to the four-momenta of the generated particles. In case of pions, the parametrisation included a dependence on the decay radius as well, in order to be able to describe pions coming from the decay of long lifetime particles such as K^0_S.

[1] Charge conjugated states are implicitly included.

[2] Throughout this paper, the symbol p_T is used for the transverse momentum with respect to the beam direction, and η for the pseudorapidity.

3 Hadron identification

The possibility for separating kaons, protons and pions enhances the observation potential of many B-hadron final states in the ATLAS experiment [12]. Monte Carlo studies of K/π separation using the signal shape information from the ATLAS Transition Radiation Tracker (TRT) have been previously reported in [13].

Recent test-beam data and detailed Monte Carlo simulations show that using the time-over-threshold information in the TRT data allows for an improved hadron identification, assuming that the TRT read-out would also provide the time of the trailing edge at low luminosity while preserving the output bandwidth requirements. The time-over-threshold method is described in detail in [14].

The time-over-threshold (ToT) for a single straw is defined as the width of the signal at the output of the low-threshold discriminator in the TRT front-end electronics. The ToT provides partial information on the particle energy loss in the straw gas, assuming that its dependence on the distance of closest approach of the track to the straw anode has been taken into account.

The energy loss estimator ($\langle\Delta_{ToT}\rangle$) is built on the basis of the individual ToT for all the straw hits on a given particle track, according to the procedure described in [14]. In the TRT, on average, 35 straws will be crossed by particle tracks with $p_{\rm T} > 0.5$ GeV and $|\eta| < 2.5$.

The expected K/π separation as a function of the transverse momentum is shown in Fig. 2 in units of standard deviation. Without including any pile-up effects, the K/π separation is predicted to be above one standard deviation for transverse momenta between 2 and 5 GeV, averaged over the full rapidity coverage (solid line), and above one standard deviation over a broader $p_{\rm T}$-range between 2 and 15 GeV at $|\eta| = 0.3$ (dotted line).

In order to study physics processes in the ATLAS experiment, the mean and the sigma of the $\langle\Delta_{ToT}\rangle$ distributions, well described by gaussians, were parameterised for pions, kaons and protons as a function of $p_{\rm T}$ and η over the full acceptance region of the ATLAS TRT [15].

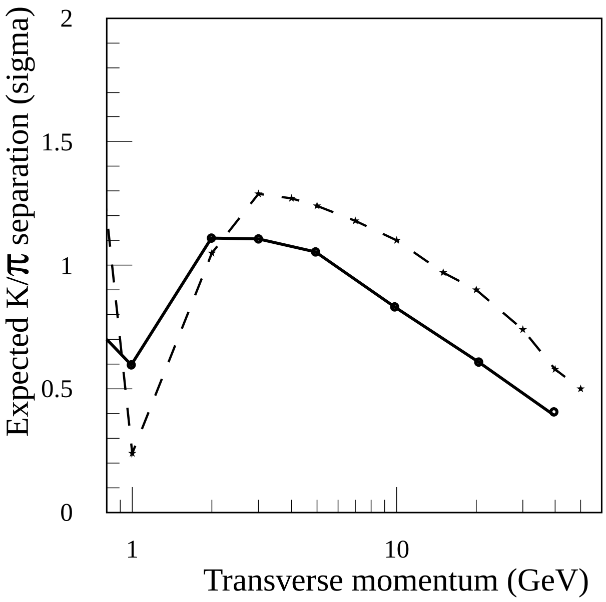

Figure 2: Expected K/π separation in units of standard deviation in the ATLAS TRT as a function of transverse momentum (no pile-up effects included). The separation is shown as an average over the full rapidity coverage (solid line) and at $|\eta| = 0.3$ (dotted line).

4 Analysis

4.1 Event selection

The event selection cuts are summarised in Table 1. The cuts on the transverse momentum of the particles and the loose cut on the B-candidate mass emulated the suggested second level trigger requirements. The other selection criteria were based on the quality of the B-vertex fit, on the long lifetime of the B meson (the reconstructed B vertex was required to be separated from the primary vertex with at least 100 μm in the transverse plane), on the rejection of events in which two of the particle pairs formed masses close to light resonance masses, and on the probability that the three particles formed a KKπ combination. The last selection criterium is explained in more detail in Section 4.2. The resolution of the decay length in the transverse plane was 72 μm.

No.	Selection	Signal efficiency	Background efficiency
1.	p_T(tracks) > 1.5 GeV	50.9%	68.8%
2.	4 GeV $< M$(B) $<$6 GeV	97.7%	53.1%
3.	χ^2(triplet vertex fit) < 2	83.6%	68.4%
4.	p_{T}(B) > 10 GeV	80.1%	22.6%
5.	Vertex detachment > 0.1mm	58.3%	0.3%
6.	$\mathcal{P}(dE/dx) > 0.1$	87.8%	76.3%
7.	m_{13}^2 and $m_{23}^2 > 2.5$ GeV^2	74.4%	35.9%
8.	5.16 GeV $<$ M(B) $<$ 5.45 GeV	91.2%	5.8%
	Overall	11.6%	$2.8 \cdot 10^{-4}$ %

Table 1: The signal and background efficiency of each selection cut. The cuts 1-8 were applied in sequence, and the efficiency of cut N is given relative to the remaining sample ($N - 1$ cuts applied).

The overall signal efficiency was found to be 11.6%, while the background efficiency was $2.8{\cdot}10^{-4}$ %. The study of the background rejection was limited by the statistics of the simulated background sample (one million inclusive $\mathrm{b\bar{b}} \to \mu$6X events, where μ6 denotes the level-1 trigger requirements for the muon). The generated background consisted of the default decay channels in PYTHIA 5.7.

4.2 Use of the dE/dx information

The selection criteria discussed in Section 4.1 reduce the background by six orders of magnitude, while preserving about 12% of the signal, as it is shown in Table 1. In this section, the use of the dE/dx information is explained in more detail.

For a charged particle track with a given p_{T} and η, the $dE/dx_{actual}(p_{\mathrm{T}},\eta)$ was simulated using the sigma and the mean provided by the parametrisation (see Section 3):

$$\frac{dE}{dx}\Big|_{actual}(p_{\mathrm{T}},\eta) = \mathrm{mean}(\langle\Delta_{ToT}\rangle)(p_{\mathrm{T}},\eta) + \mathrm{RND} * \sigma(\langle\Delta_{ToT}\rangle)(p_{\mathrm{T}},\eta),$$

where RND is a gaussian-distributed pseudo-random number.

For any given triplet of particles, two positively and one negatively charged — candidates for the decay products of the B^+ — the χ^2 distribution was constructed according to :

$$\chi^2 = \sum_{i=1}^{3}\left[\frac{\frac{dE}{dx}\big|_{exp} - \frac{dE_i}{dx}\big|_{act}}{\sigma_i}\right]^2$$

where the index i labels the individual particles in the triplet and $\frac{dE}{dx}|_{exp}$ is the mean value of the dE/dx distribution for pions (if the particle had a negative charge) or for kaons (if the particle had a positive charge). The obtained χ^2 probability distribution for three degrees of freedom is shown in Fig. 3. The background misidentification probability as a function of the signal efficiency is shown in Fig. 4, when the cut on the dE/dx χ^2 probability was varied.

4.3 Results

The number of signal events, passing the ATLAS level-1 trigger, was estimated as:

$$N^{\mathrm{prod}}_{\mathrm{signal}} = \sigma(\mathrm{pp}\to\mathrm{b\bar{b}}\to\mu6\mathrm{X})\cdot\mathcal{B}\mathrm{r}(\mathrm{b}\to\mathrm{B}^+)\cdot\mathcal{B}\mathrm{r}(\mathrm{B}^+\to\mathrm{K}^+\mathrm{K}^+\pi^-)\cdot\int\mathcal{L}\mathrm{dt},$$

and the number of observed events as:

$$N^{\mathrm{obs}}_{\mathrm{signal}} = N^{\mathrm{prod}}_{\mathrm{signal}}\cdot\epsilon_{\mathrm{rec}}\cdot\epsilon_{\mathrm{id}},$$

where the cross-section after the level-1 trigger is $\sigma(\mathrm{pp}\to\mathrm{b\bar{b}}\to\mu6\mathrm{X}) = 2.3\mu\mathrm{b}$, $\mathcal{B}r(\mathrm{b}\to\mathrm{B}^+) = 39.7\%$, the integrated luminosity is $\int\mathcal{L}dt = 30\mathrm{fb}^{-1}$ (corresponding to three years of LHC data-taking at the initial low luminosity), the signal reconstruction efficiency is $\epsilon_{\mathrm{rec}} = 11.6\%$, the muon efficiency is $\epsilon_{\mathrm{id}}(\mu6) = 0.85$, and the pion and kaon reconstruction efficiencies are $\epsilon_{\mathrm{id}}(\pi,\mathrm{K}) = 0.90$.

The number of background events was estimated as:

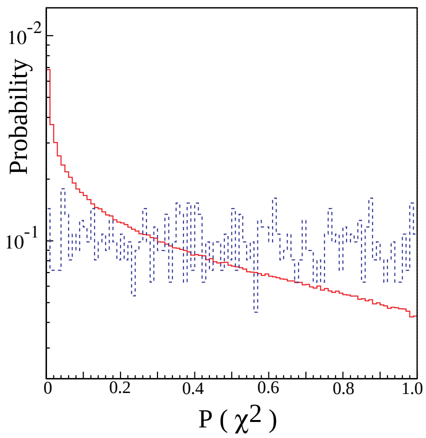

Figure 3: The χ^2 probability distribution for three degrees of freedom for the signal (dotted line) and the background (solid line), after applying the proposed second level trigger requirements (see Sect. 2). Both distributions were normalised to unity.

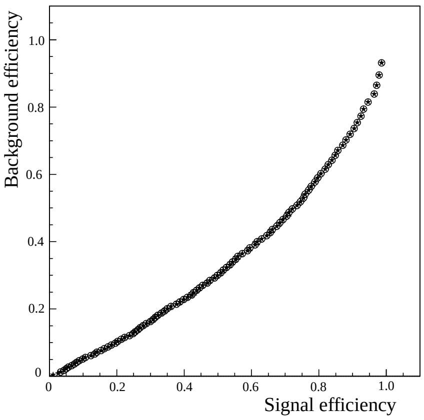

Figure 4: Background misidentification probability as a function of the signal efficiency, when the cut on the dE/dx χ^2 probability was varied. The proposed second level trigger requirements were applied to the event sample first (see Sect. 2).

$$N_{\rm bg}^{\rm prod} = \sigma(\rm pp \to b\bar{b} \to \mu 6X) \cdot \int \mathcal{L} dt.$$

The number of produced background events was thus $N_{\rm bg}^{\rm prod} = 6.9 \cdot 10^{10}$ for 30 $\rm fb^{-1}$. Using $\epsilon_{\rm rec} = 2.8\ 10^{-4}\%$ and $\epsilon_{\rm id}(\mu 6) = 0.85$, $\epsilon_{\rm id}(\pi, \rm K) = 0.90$, the number of observed background events was $N_{\rm bg}^{\rm obs} = 1.2 \cdot 10^5$.

An upper limit of

$$\mathcal{B}r(\rm B^+ \to K^+K^+\pi^-) = 3.4 \cdot 10^{-7}$$

can be established at a 95% CL after three years of data-taking at the low luminosity. If one requires a signal significance of five standard deviations, a signal with a branching ratio of:

$$\mathcal{B}r(\rm B^+ \to K^+K^+\pi^-) = 8.8 \cdot 10^{-7}$$

can be observed with the same statistics.

4.4 Limits on the R-parity violating couplings

The $\rm b \to ss\bar{d}$ decay rate induced by the R-parity violating couplings was estimated in Ref. [6] to be :

$$\Gamma(\mathrm{b} \to \mathrm{ss\bar{d}}) = \frac{\mathrm{m_b^5 f_{QCD}^2}}{512(2\pi)^3 \mathrm{m}_{\tilde{\nu}}^2} \left(\left| \sum_{\mathrm{i=1}}^{3} \lambda'_{\mathrm{i32}} \lambda'^{*}_{\mathrm{i21}} \right|^2 + \left| \sum_{\mathrm{i=1}}^{3} \lambda'_{\mathrm{i12}} \lambda'^{*}_{\mathrm{i23}} \right|^2 \right),$$

where m_{b} is the b-quark mass, $f_{\mathrm{QCD}} = (\alpha_s(\mathrm{b})/\alpha_s(m_{\tilde{\nu}}))^{24/23}$, $m_{\tilde{\nu}}$ is the sneutrino mass and λ' are dimensionless couplings.

It was estimated in Ref. [6] that a fourth (or less) of the $\mathrm{b} \to \mathrm{ss\bar{d}}$ transitions leads to $\mathrm{B^{\pm} \to K^{\pm}K^{\pm}}$ + (no strange) decay channels. Final states including $\mathrm{K^{\pm}K^{\pm}}$ + (no strange) can be produced via one or two excited kaons with respective proportions $\mathrm{K^*K^* \geq K^*K \geq KK}$. It was assumed, pessimistically, that direct $\mathrm{K^{\pm}K^{\pm}}$ decay represents a third of the total $\mathrm{K^{\pm}K^{\pm}}$ + (no strange) decays, thus 1/12 of the $\mathrm{b} \to \mathrm{ss\bar{d}}$ transitions. Using this estimation with the 95 % CL ATLAS bound and, as in Ref. [6], $m_{\mathrm{b}} = 4.5$ GeV, $f_{\mathrm{QCD}} = 2$, $m_{\tilde{\nu}} = 100$ GeV, $\tau_{\mathrm{B^+}} = 1.65$ ps, a limit on the couplings will be:

$$\sqrt{\left| \sum_{i=1}^{3} \lambda'_{i32} \lambda'^{*}_{i21} \right|^2 + \left| \sum_{i=1}^{3} \lambda'_{i12} \lambda'^{*}_{i23} \right|^2} < 5.3 \cdot 10^{-5}.$$

This limit should be considered as a rough estimate, obtained using very pessimistic assumptions on the relative decay probabilities in order to maximize the relative fraction of the decay mode $\mathrm{B^+ \to K^+K^+}\pi^-$. The limit is nevertheless an order of magnitude better than the corresponding OPAL limit in Ref. [8]. Complementary measurements come from neutrino data [16] which give values for individual λ' couplings for different neutrino mass scenarios.

5 Comparison to the other experiments

If the branching ratio of the decay $\mathrm{B^+ \to K^+K^+}\pi^-$ is in the range of the MSSM or THDM predictions ($\mathcal{O}(10^{-7})$), the event yield of the PEP-II and KEKB B-factories is only a few events with an integrated luminosity of 30 $\mathrm{fb^{-1}}$ to 100 $\mathrm{fb^{-1}}$. Therefore these investigations would not seem feasible for BaBar and Belle in the R-parity conserving scenarios.

The hadron colliders Tevatron and LHC have much larger $\mathrm{b\bar{b}}$ cross sections, which opens up the opportunity to study $\mathrm{b} \to \mathrm{ss\bar{d}}$ transitions. For CDF it was assumed that the trigger efficiency is a ten times better than the ATLAS trigger efficiency, due to the possibility of triggering on purely hadronic final states. It was assumed that CDF has the same signal reconstruction efficiency as ATLAS. The K/π separation capability is similar in the two experiments for transverse momenta above 1.3 GeV. ATLAS has a larger pseudorapidity acceptance than CDF, but on the other hand the final states are more central with less initial state gluon radiation at the smaller center-of-mass energy. The estimated overall efficiency was consistent with the results on experimentally similar decays [17]. Using these assumptions, one can estimate that CDF could set an upper limit of $7.9 \cdot 10^{-7}$ at 95% CL with 2 fb^{-1}. A signal significance of five standard deviations could be achieved if the branching ratio were $2.0 \cdot 10^{-6}$.

The LHCb experiment has the advantage of being able to trigger on purely hadronic final states, and having a superior K/π separation thanks to its RICH detectors. Based on the results presented in Table 15.11 in Ref. [18], it was estimated that LHCb could observe a five-standard-deviation signal if the branching ratio were $1.0 \cdot 10^{-7}$, given the statistics of three years' running at the nominal LHCb luminosity of $2 \cdot 10^{-32}$ cm^{-2} s^{-1} . The 95% CL upper limit for the branching ratio would be $4.0 \cdot 10^{-8}$.

These results should be taken as crude estimations, which were based on the publicly available information on the detector and accelerator performance.

6 Summary and outlook

A feasibility study of reconstructing the decay $B^+ \to K^+K^+\pi^-$ in the ATLAS experiment at LHC has been presented. The obtained 95% CL upper limit of

$$\mathcal{B}r(B^+ \to K^+K^+\pi^-) = 3.4 \cdot 10^{-7}$$

approaches the range of branching fractions predicted by MSSM or THDM scenarios. In R-parity violating models, branching ratios could be as large as 10^{-4}. ATLAS could thus contribute in the measurements of some of the R-parity violating couplings. Given the upper limit above, the following limit can be set on the couplings:

$$\sqrt{\left|\sum_{i=1}^{3} \lambda'_{i32}\lambda'^{*}_{i21}\right|^2 + \left|\sum_{i=1}^{3} \lambda'_{i12}\lambda'^{*}_{i23}\right|^2} < 5.3 \cdot 10^{-5}.$$

The presented analysis of the $B^+ \to K^+K^+\pi^-$ decay shows that the ATLAS experiment will be able to set a new upper limit on the branching ratio, which will be more than two orders of magnitude lower than the present estimate. The limit on the relation that constrains the λ' couplings of the MSSM with R-parity violation will also be improved by an order of magnitude. This analysis considered only the direct decay $B^+ \to K^+K^+\pi^-$, but ATLAS should be able to increase the statistics by searching for final states with K^*K^* and K^*K.

Combining all the results, the LHC experiments will contribute significantly to the search and measurements of physics beyond the Standard Model using the $B^+ \to K^+K^+\pi^-$ decay channel.

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