I. INTRODUCTION

The observed $B^0_s$ and $\bar{B}^0_s$ particles are linear combinations of the two mass eigenstates with masses $m_H$ and $m_L$ and a mass difference of $\Delta m_s$. Transitions between the two flavor eigenstates are allowed due to non-conservation of flavor in weak-current interactions and will occur with a frequency proportional to $\Delta m_s$. Together with the mass difference $\Delta m_d$ of the $B^0_s$ system, which has already been measured with high accuracy ($\Delta m_d = 0.502 \pm 0.007 \text{ps}^{-1}$) [1], the measurement of $\Delta m_s$ is an important ingredient for the precise determination of the side $|V_{td}|$ of the CKM unitarity triangle. The direct determination of $V_{td}$ and $V_{ts}$ from $\Delta m_d$ and $\Delta m_s$ is hampered by hadronic uncertainties. These uncertainties partially cancel in the ratio of mass differences

$$\frac{\Delta m_s}{\Delta m_d} = \xi^2 \frac{M_{B_d}}{M_{B_s}} \frac{|V_{ts}|^2}{|V_{td}|} \quad (1)$$

Using the experimentally-measured masses $M_B$ and a value for the factor $\xi$, which can be computed in lattice QCD, the constraint from the ratio $\Delta m_s/\Delta m_d$ is more effective in limiting the position of the apex of the unitarity triangle than the value obtained by $\Delta m_d$ measurements alone.

$B^0_s$ oscillations have been observed recently at the Fermilab Tevatron collider. Whereas the D0 collaboration is reporting a two-sided bound $17 < \Delta m_s < 21 \text{ps}^{-1}$ at 90% CL [2], CDF presents the first measurement of the $B^0_s$-$\bar{B}^0_s$ oscillation frequency finding a signal for $\Delta m_s = 17.33 \pm 0.42 \text{ (stat)} \pm 0.07 \text{ (sys)}$ at 95% CL [3]. Both results are consistent with the prediction of the Standard Model for the upper bound of $\Delta m_s \sim 25 \text{ ps}^{-1}$ [4].

The work presented here gives an updated estimate for the $\Delta m_s$ sensitivity from the ATLAS experiment using Monte Carlo events of the $B^0_s$ hadronic channels $B^0_s \rightarrow D^+_s \pi^+$ and $B^0_s \rightarrow D^+_s a_1$ with $D^+_s \rightarrow \phi(K^+ K^-) \pi^-$ and $a_1^+ \rightarrow \pi^+ \pi^- \pi^+$, the following sections contain a brief discussion of the event selection, analysis cuts and the most important kinematic distributions of the $B^0_s$ candidates.

II. TOOLS AND DETECTOR LAYOUT

A detailed description of the generation, simulation, reconstruction and analysis software tools used for this study as well as a short characterization of the properties of the ATLAS Inner Detector layout is given in [5]. The ATLAS B-physics trigger with various strategies for B-trigger selections is described in [6].

III. EVENT SELECTION AND ANALYSIS RESULTS

In the offline analysis the $B^0_s$ meson is reconstructed from its decay products, applying kinematical cuts on tracks, kinematical and mass cuts on intermediate particles like $D^-_s$ and $\phi$. A vertex fit includes mass constraints and requires that the total momentum of the $B^0_s$ vertex points to the primary vertex and the momentum of the $D^-_s$ vertex points to the $B^0_s$ vertex.

To improve the purity of the sample cuts on properties of the $B^0_s$ candidates like proper time, impact parameter, transverse momentum and mass cuts are imposed.

For the $B^0_s \rightarrow D^-_s \pi^+$ channel Figure 1 shows the fitted invariant mass distribution $M_{K^- K^+ \pi^+}$ with a mass resolution of $\sigma_{B_s} = 42.5$ MeV (single Gauss fit).

FIG. 1: Reconstructed $B^0_s$ invariant mass distribution normalized to 10 fb$^{-1}$. The core of the distribution is fitted with a single Gauss function.

The proper time of the reconstructed $B^0_s$ candi-
dates is computed from the reconstructed transverse decay length $d_{xy}$, the $B_s^0$ mass and the $B_s^0$ transverse momentum $p_T$. Parameterized with the sum of two Gauss functions around the same mean value the widths of the two Gaussians resulting from the fit are $\sigma_1 = (70.3 \pm 3.9)$ fs for the core fraction of 54.7% and $\sigma_2 = (156.1 \pm 6.8)$ fs for the rest of the tail part of the distribution.

The likelihood of the total sample is written as

$$L(\Delta m_s, \Delta \Gamma_s) = \prod_{k=1}^{N_{ch}} \prod_{i=1}^{N_{ev}} \text{pdf}_k(t_i, \mu_i)$$  \hspace{1cm} (3)$$

The index $k = 1$ denotes the $B_s^0 \to D_s^- \pi^+$ channel and $k = 2$ the $B_s^0 \to D_s^- a_1^+$ channel, $N_{ev}^k$ is the total number of events of type $k$, and $N_{ch} = 2$. See [5] for detailed information on the building of the probability density functions.

V. CREATION OF THE $B_s^0$ ‘DATA SAMPLE’

A simplified Monte Carlo method is applied to generate a $B_s^0$ sample using the numbers of reconstituted $B_s^0$ events and kinematic distributions obtained from the simulation studies in Ref. [5] as input parameters. $B_s^0$ signal events oscillating with a given frequency $\Delta m_s$ (e.g. $\Delta m_s = 100$ ps$^{-1}$, which is far off the expected value for $\Delta m_s$), together with $N_{B_d} = N_{B_s}^1 + N_{B_s}^2$ background events oscillating with frequency $\Delta m_d$ and $N_{cb} = N_{cb}^1 + N_{cb}^2$ combinatorial events (no oscillations) are generated according to Eq. 2.

VI. RESULTS ON $\Delta M_s$ MEASUREMENT LIMITS

The $\Delta m_s$ measurement limits are obtained applying the amplitude fit method [8] to the ‘data sample’ generated as described in the previous section. According to this method a new parameter, the $B_s^0$ oscillation amplitude $A$, is introduced in the likelihood function by replacing the term $\mu_0 \cos \Delta m_s t_0$, with $\mu_0 A \cos \Delta m_s t_0$, in the $B_s^0$ probability density function given in Eq. 2. For each value of $\Delta m_s$, the new likelihood function is minimized with respect to $A$, keeping all other parameters fixed, and a value $A \pm \sigma_A^{\text{stat}}$ is obtained. One expects, within the estimated uncertainty, $A = 1$ for $\Delta m_s$ close to its true value, and $A = 0$ for $\Delta m_s$ far from the true value. A 5 $\sigma$ measurement limit is defined as the value of $\Delta m_s$ for which $1/\sigma_A = 5$, and a sensitivity at 95% confidence level as the value of $\Delta m_s$ for which $1/\sigma_A = 1.645$. Limits are computed with the statistical uncertainty $\sigma_A^{\text{stat}}$. A detailed investigation on the systematic uncertainties $\sigma_A^{\text{sys}}$, which affects the measurement of the $B_s^0$ oscillation, is presented.
For the nominal set of parameters (as defined in the previous sections), $\Delta \Gamma_s = 0$ and an integrated luminosity of 30 fb$^{-1}$ the amplitude $\pm 1\sigma_{\text{stat}}^A$ is plotted as a function of $\Delta m_s$ in Fig. 3. The 95% CL sensitivity to measure $\Delta m_s$ is found to be 30.5 ps$^{-1}$. This value is given by the intersection of the dashed line, corresponding to $1.645 \sigma_{\text{stat}}^A$ with the $A = 1$ horizontal line.

From Fig. 4, which shows the significance of the measurement $S(\Delta m_s) = 1/\sigma_A$ as a function of $\Delta m_s$, the 5$\sigma$ measurement limit is found to be 22 ps$^{-1}$.

The dependence of the $\Delta m_s$ measurement limits on the integrated luminosity is shown in Fig. 5, with the numerical values given in Table I.

| Lumi (fb$^{-1}$) | 5$\sigma$ limit | 95% CL sensitivity (ps$^{-1}$) |
|-----------------|-----------------|-----------------------------|
| 5               | 13.2            | 23.8                        |
| 10              | 16.5            | 26.5                        |
| 20              | 20.0            | 29.0                        |
| 30              | 21.9            | 30.5                        |

TABLE I: The dependence of $\Delta m_s$ measurement limits on the integrated luminosity.

In this summary the performance of the $B_s^0 \rightarrow D^-_s (\phi \pi^-) \pi^+$ channel and extrapolated numbers for $B_s^0 \rightarrow D^-_s a_1^+$ channel are used to calculate the 95% CL exclusion and 5$\sigma$ measurement limits of the $B_s^0$ oscillation frequency as a function of the integrated luminosity collected with the ATLAS detector. The limits are updated for the detector geometry of “initial layout” using full Rome statistics, but only statistical errors are taken into account. With an integrated luminosity from 10 to 20 fb$^{-1}$ a 5$\sigma$ measurement for a range of $16.5 < \Delta m_s < 20$ ps$^{-1}$ is possible, covering the recent results from the Tevatron collider.

The values obtained in this note for the measurement limits should be re-evaluated, taking into account changes in the detector geometry, especially “complete detector layout”, and the evolving simulation and reconstruction software. $D^-_s a_1^+$ and exclusive $B_s^0$ background channels will be analyzed independently and investigations looking at the performance of other interesting $B_s^0-B_s^0$ mixing channels, which might be included in the analysis, will be carried out.

VII. CONCLUSIONS

In this summary the performance of the $B_s^0 \rightarrow D_s^- (\phi \pi^-) \pi^+$ channel and extrapolated numbers for $B_s^0 \rightarrow D_s^- a_1^+$ channel are used to calculate the 95% CL exclusion and 5$\sigma$ measurement limits of the $B_s^0$ oscillation frequency as a function of the integrated luminosity collected with the ATLAS detector. The limits are updated for the detector geometry of “initial layout” using full Rome statistics, but only statistical errors are taken into account. With an integrated luminosity from 10 to 20 fb$^{-1}$ a 5$\sigma$ measurement for a range of $16.5 < \Delta m_s < 20$ ps$^{-1}$ is possible, covering the recent results from the Tevatron collider.

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FIG. 6: The dependence of $\Delta m_s$ measurement limits on $\Delta \Gamma_s/\Gamma_s$. 

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