Prospects of the measurement of B_s^0 oscillations with the ATLAS detector at LHC

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An estimation of the sensitivity to measure B_s^0-$\bar{B}_s^0$ oscillations with the ATLAS detector is given for the detector geometry of "initial layout". The Δm_s reach is derived from unbinned maximum likelihood amplitude fits using B_s^0 events generated with a simplified Monte Carlo method.

I. INTRODUCTION

The observed B_s^0 and $\bar{B}_s^0$ particles are linear combinations of the two mass eigenstates with masses m_H and m_L and a mass difference of Δm_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 Δm_s. Together with the mass difference Δm_d of the B_d^0 system, which has already been measured with high accuracy ($\Delta m_d = 0.502 \pm 0.007 \text{ps}^{-1}$[1]), the measurement of Δm_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 Δm_d and Δm_s is hampered by hadronic uncertainties. These uncertainties partially cancel in the ratio of mass differences

$$\frac{\Delta m_s}{\Delta m_d} = \xi^2 \, \frac{M_{B_s^0}}{M_{B_d^0}} \, \left| \frac{V_{ts}}{V_{td}} \right|^2 \qquad (1)$$

Using the experimentally-measured masses M_B and a value for the factor ξ, 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 Δm_d measurements alone.

B_s^0 oscillations have been observed recently at the Fermilab Tevatron collider. Whereas the DØ 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_s^0-$\bar{B}_s^0$ oscillation frequency finding a signal for $\Delta m_s = 17.33\ ^{+0.42}_{-0.21}\,(\text{stat}) \pm 0.07\,(\text{sys})$ 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 Δm_s sensitivity from the ATLAS experiment using Monte Carlo events of the B_s^0 hadronic channels $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^- a_1^+$ with $D_s^- \to \phi(K^+ K^-) \pi^-$ and $a_1^+ \to \pi^+ \pi^- \pi^+$. the following sections contain a brief discussion of the event selection, analysis cuts and the most important kinematic distributions of the B_s^0 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_s^0 meson is reconstructed from its decay products, applying kinematical cuts on tracks, kinematical and mass cuts on intermediate particles like D_s^- and ϕ. A vertex fit includes mass constraints and requires that the total momentum of the B_s^0 vertex points to the primary vertex and the momentum of the D_s^- vertex points to the B_s^0 vertex. To improve the purity of the sample cuts on properties of the B_s^0 candidates like proper time, impact parameter, transverse momentum and mass cuts are imposed. For the $B_s^0 \to D_s^- \pi^+$ channel Figure 1 shows the fitted invariant mass distribution $M_{KK\pi\pi}$ with a mass resolution of $\sigma_{B_s} = 42.5$ MeV (single Gauss fit).

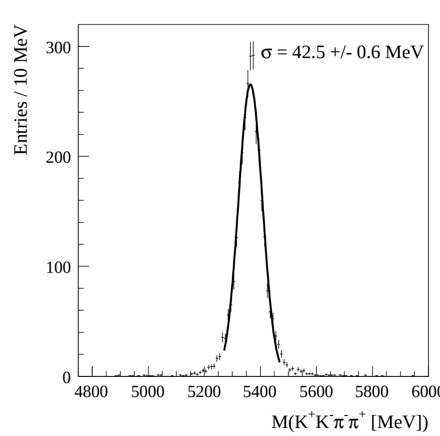

FIG. 1: Reconstructed B_s^0 invariant mass distribution normalized to 10 fb^{-1}. The core of the distribution is fitted with a single Gauss function.

The proper time of the reconstructed B_s^0 candidates is computed from the reconstructed transverse decay length d_{xy}, the B_s^0 mass and the B_s^0 transverse momentum $p_{\rm T}$. 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.

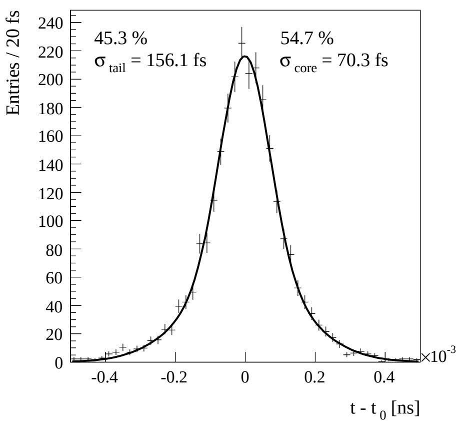

FIG. 2: Proper-time resolution normalized to 10 fb^{-1} for B_s^0 from $B_s^0 \to D_s^- \pi^+$ decays and fitted with the sum of two Gauss functions around a common mean value.

The estimation of the maximum value of Δm_s measurable with ATLAS is considering B_s^0 candidates from the $D_s^- \pi^+$ and $D_s^- a_1^+$ channels. The detailed analysis is done for the $B_s^0 \to D_s^- \pi^+$ channel, whereas numbers for the $B_s^0 \to D_s^- \, a_1^+$ signal and B_d^0 exclusive background channels are estimated extrapolations. More details on the event selection including cut values, kinematical resolutions, expected number of events for signal and background channels can be found in [5].

IV. BUILDING OF THE LIKELIHOOD FUNCTION

The probability density to observe an initial B_j^0 meson $(j = d, \ s)$ decaying at time t_0 after its creation as a $\bar{B}_j^0$ meson is given by

$$p_j(t_0, \ \mu_0) = \frac{\Gamma_j^2 - \left(\frac{\Delta\Gamma_j}{2}\right)^2}{2\,\Gamma_j} \, \mathrm{e}^{-\Gamma_j t_0} \times \left(\cosh \frac{\Delta\Gamma_j t_0}{2} + \mu_0 \cos \Delta m_j t_0\right) \quad (2)$$

where $\Delta\Gamma_j = \Gamma_{\rm H}^j - \Gamma_{\rm L}^j$, $\Gamma_j = (\Gamma_{\rm H}^j + \Gamma_{\rm L}^j)/2$ and $\mu_0 = -1$.
For the unmixed case (an initial B_j^0 meson decaying as a B_j^0 meson at time t_0), the probability density is obtained by setting $\mu_0 = +1$ in Eq. 2.

Experimental effects like the wrong tag fraction and the resolution of the reconstructed proper time of the B_s^0 modify the probability function. Exclusive oscillating background channels and non-oscillating combinatorial background are taken into account as fractions of the probability density called pdf$_k$.
The likelihood of the total sample is written as

$$\mathcal{L}(\Delta m_s, \Delta\Gamma_s) = \prod_{k=1}^{N_{\rm ch}} \prod_{i=1}^{N_{\rm ev}^k} \mathrm{pdf}_k(t_i, \mu_i) \qquad (3)$$

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, $N_{\rm ev}^k$ is the total number of events of type k, and $N_{\rm ch} = 2$. 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 reconstructed 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 Δm_s (e.g. $\Delta m_s = 100$ ps^{-1}, which is far off the expected value for Δm_s), together with $N_{B_d^0} = N_{B_d^0}^1 + N_{B_d^0}^2$ background events oscillating with frequency Δm_d and $N_{\rm cb} = N_{\rm cb}^1 + N_{\rm cb}^2$ combinatorial events (no oscillations) are generated according to Eq. 2.

VI. RESULTS ON ΔM_S MEASUREMENT LIMITS

The Δm_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 $\mathcal{A}$, is introduced in the likelihood function by replacing the term '$\mu_0 \cos \Delta m_s t_0$' with '$\mu_0 \mathcal{A} \cos \Delta m_s t_0$' in the B_s^0 probability density function given in Eq. 2. For each value of Δm_s, the new likelihood function is minimized with respect to $\mathcal{A}$, keeping all other parameters fixed, and a value $\mathcal{A} \pm \sigma_{\mathcal{A}}^{\rm stat}$ is obtained. One expects, within the estimated uncertainty, $\mathcal{A} = 1$ for Δm_s close to its true value, and $\mathcal{A} = 0$ for Δm_s far from the true value. A 5 σ measurement limit is defined as the value of Δm_s for which $1/\sigma_{\mathcal{A}} = 5$, and a sensitivity at 95% confidence level as the value of Δm_s for which $1/\sigma_{\mathcal{A}} = 1.645$. Limits are computed with the statistical uncertainty $\sigma_{\mathcal{A}}^{\rm stat}$. A detailed investigation on the systematic uncertainties $\sigma_{\mathcal{A}}^{\rm syst}$, which affects the measurement of the B_s^0 oscillation, is presented

in [7].
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 $\pm 1\sigma_{\mathcal{A}}^{\rm stat}$ is plotted as a function of Δm_s in Fig. 3. The 95% CL sensitivity to measure Δm_s is found to be 30.5 ps^{-1}. This value is given by the intersection of the dashed line, corresponding to 1.645 $\sigma_{\mathcal{A}}^{\rm stat}$ with the $\mathcal{A} = 1$ horizontal line.

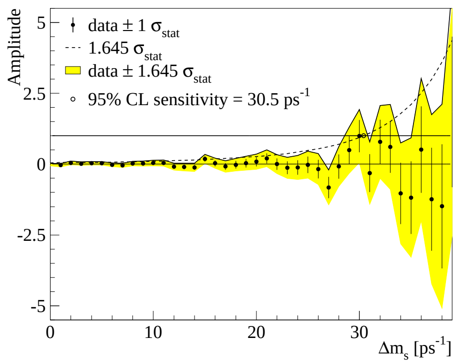

FIG. 3: The B_s^0 oscillation amplitude as a function of Δm_s for an integrated luminosity of 30 fb^{-1} for a specific Monte Carlo experiment.

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

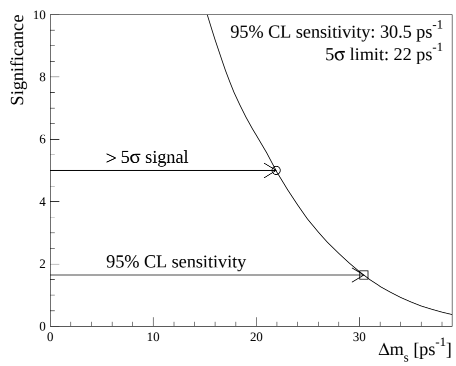

FIG. 4: The measurement significance as a function of Δm_s for an integrated luminosity of 30 fb^{-1}.

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

The dependence of the Δm_s measurement limits on $\Delta\Gamma_s/\Gamma_s$ is determined for an integrated luminosity of 30 fb^{-1}, other parameters having their nominal value. The $\Delta\Gamma_s/\Gamma_s$ is used as a fixed parameter in the amplitude fit method. As shown in Fig. 6 no sizeable effect is seen up to a $\Delta\Gamma_s/\Gamma_s$ of 50%.

Lumi (fb^{-1})	5σ limit (ps^{-1})	95% CL sensitiv. (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 Δm_s measurement limits on the integrated luminosity.

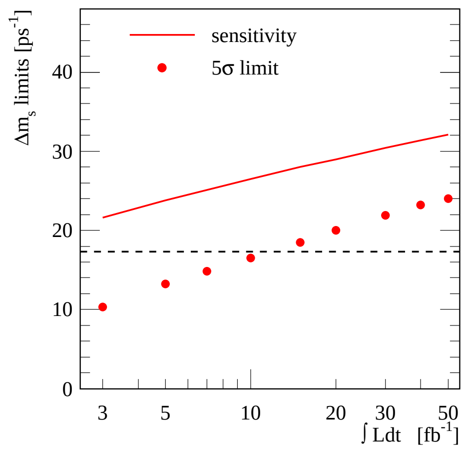

FIG. 5: The dependence of Δm_s measurement limits on the integrated luminosity. The dotted horizontal line gives the CDF measurement [3].

VII. CONCLUSIONS

In this summary the performance of the $B_s^0 \to D_s^-(\phi\,\pi^-)\,\pi^+$ channel and extrapolated numbers for $B_s^0 \to D_s^-\,a_1^+$ channel are used to calculate the 95% CL exclusion and 5 σ 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 σ 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_d^0 background channels will be analyzed independently and investigations looking at the performance of other interesting B_s^0-$\bar{B}_s^0$ mixing channels, which might be included in the analysis, will be carried out.

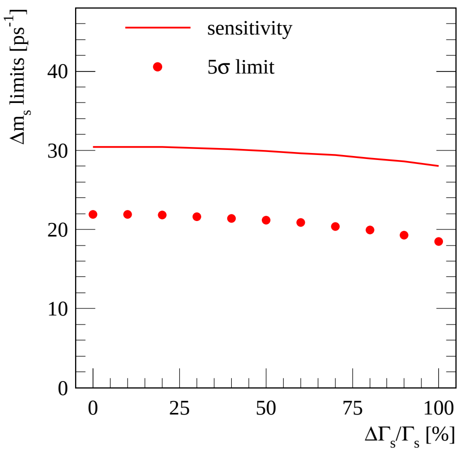

FIG. 6: The dependence of Δm_s measurement limits on $\Delta\Gamma_s/\Gamma_s$.

Acknowledgments

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